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Technical Report

Environmental Life Cycle Implications of Using Bagasse-Derived Ethanol as a Gasoline Oxygenate in Mumbai (Bombay)

Kiran L. Kadam

Prepared for the National Energy Technology Laboratory
Pittsburgh, Pennsylvania, USA and
USAID, New Delhi, India

National Renewable Energy Laboratory

1617 Cole Boulevard
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EXECUTIVE SUMMARY

Background

Bagasse is the fibrous residue generated during sugar production and can be a desirable feedstock for fuel ethanol production. About 15%–25% of the bagasse is left after satisfying the mills' energy requirements, and this excess bagasse can be used in a bioconvesion process to make ethanol. It is estimated that a 23 million L/yr (~6 million gal/yr) ethanol facility is feasible by combining excess bagasse from three sugar mills in Maharashtra state. The annual gasoline consumption in Mumbai is estimated to be 400–500 million L, and the plant could supply about half of the ethanol demand, assuming that all gasoline is sold as an E10 fuel, a blend of 90% gasoline and 10% ethanol by volume.

This study discusses the potential benefits of using bagasse-derived fuel ethanol in India. This strategy is pertinent to the Indian scene because it can: 1) reduce the net emissions of carbon dioxide, 2) improve air quality in major metropolitan areas such as Mumbai when used as an oxygenate additive to gasoline, 3) spur rural economic development, and 4) improve the country's energy security by reducing its reliance on foreign oil and associated risks.

Study Objective and Results

The study objective is to conduct a life cycle assessment (LCA) to quantify the environmental benefits of using bagasse-derived ethanol as a gasoline oxygenate in Mumbai. The LCA results would serve as a basis for deploying bagasse-to-ethanol production in Maharashtra, because positive environmental benefits—both in terms of local air quality and climate change—align with USAID's mission and objectives.

The LCA performed in this study demonstrates the potentially significant benefits of using ethanol derived from bagasse in Maharashtra. The overall results revealed a fundamental difference between Scenario 1 (burning excess bagasse as a disposal option) and Scenario 2 (conversion to ethanol) in terms of energy derived from renewable sources and the concomitant benefits of reduced greenhouse gas emissions. In particular, lower net values for the ethanol scenario were observed for the following:

- Carbon monoxide
- Hydrocarbons (except methane)
- SO_x and NO_x
- Particulates
- Carbon dioxide and methane
- Fossil energy consumption

Hence, implementing the ethanol scenario would reduce air emissions and fossil energy consumption. Reduced carbon dioxide and methane emissions, although not regulated or mandated by state or national laws, are also desirable attributes. The lower greenhouse potential of Scenario 2 can be important if greenhouse gas trading is possible, or in the case of Joint

Implementation because India is a developing country. Additional drivers are the lower values observed for the following six impact assessment categories for the ethanol scenario, when compared to the burning scenario:

- Greenhouse potential
- Depletion of natural resources
- Air acidification potential
- Eutrophication potential
- Human toxicity potential
- Air odor potential

Hence, the ethanol scenario distinguishes itself by demonstrating lower burdens than the burning scenario for key environmental criteria, both regulated and unregulated.

Next Phase of the Project

The next phase should address how to deploy this option in India by capitalizing on the environmental benefits of diverting the excess bagasse to ethanol production. The action plan would involve institutional and stakeholder networking and would address deployment this technology with the help of relevant parties in India, from both the public and private sectors.

Early this year, India's Minister of Petroleum and Natural Gas approved the use of ethanol as a fuel/additive. During his recent trip to India, President Clinton signed a joint statement on cooperation between India and the United States in the areas of energy and environment; the statement has language about Clean Development Mechanism as specified under the Kyoto Protocol. Hence, these recent developments in India portend a fertile ground for deploying the bioethanol option in India.

1 INTRODUCTION

Worldwide economic development will lead to increased emissions of greenhouse gases (GHGs) well into the next century. Developing countries like India and China are expected to be major contributors to atmospheric carbon dioxide (CO_2) build-up and are potential targets for the deployment of biomass-based technologies, given the large amounts of biomass available within their borders.

India is the world's sixth largest and second fastest growing producer of greenhouse gases. In 1992, India's carbon emissions were 177 Mt (million metric tons), the third largest among non-OECD (Organization for Economic Cooperation and Development) countries. Fossil fuel energy consumption was about 7.5 quadrillion Btu, 15% of which was attributable to the transportation sector. About the same fraction of the total carbon emissions was associated with the transportation sector. Hence, significant carbon emissions arise from the use of fossil fuels for transportation in India. Vehicular emissions also contribute to local air pollution. Delhi, Mumbai (formerly Bombay), and Chennai (formerly Madras) are three of the world's ten most polluted cities. For the specific case of Mumbai, the National Environmental Engineering Research Institute in Nagpur, India, estimates that motor vehicles will contribute nearly 90% of the 255,000 t/yr of carbon monoxide (CO) emissions. Oxygenating the gasoline with ethanol can reduce CO emissions.

This report discusses the potential benefits of using bagasse-derived fuel ethanol, a strategy that is relevant to India, as it can: 1) reduce the net emissions of CO_2 into the atmosphere, 2) improve air quality in major urban centers such as Mumbai when used as either a 10% (by volume) oxygenate additive to gasoline (short-term) or as an alternative to gasoline (long-term), 3) provide rural economic development, and 4) improve the country's energy security by reducing its exposure to risks associated with foreign oil.

2 PROJECT SCOPE

The primary objective is to conduct a life cycle assessment (LCA) to quantify the environmental benefits of using bagasse-derived ethanol as a gasoline oxygenate in Mumbai. The LCA results will serve as a basis for deploying bagasse-to-ethanol production in Maharashtra, because positive environmental benefits—both in terms of local air quality and climate change—align with USAID's (U.S, Agency for International Development) mission and objectives. A brief discussion is also provided on how Joint Implementation (JI) and Clean Development Mechanism (CDM) initiatives and emissions trading, opportunities available to developing countries under the United Nations Framework Convention on Climate Change, can be used to help deploy bagasse-to-ethanol production India.

3 SUGARCANE AND SUGAR PRODUCTION

3.1 World Sugar Situation

Brazil and India are the world's two largest sugarcane (*Saccharum officinarum*) growers with production of 300 and 285 Mt/yr, respectively (Lower and Barros 1999; Singh 2000). These two countries are also expected to account for nearly 75% of the future increase in sugarcane production. World sugar consumption in 1999–2000 is estimated at 131.3 Mt, up 2% from the previous year's level, with Brazil and India contributing 19.0 and 17.9 Mt, respectively (World Bank 2000).

3.2 Sugarcane Production in India

As demonstrated in Table 1, India's leading sugarcane-producing states are Uttar Pradesh, Maharashtra, and Tamil Nadu, together accounting for about 70% of the national output (Smouse et al. 1998; Deccan Herald 1999). Although the focus of this study is Maharashtra, similar ethanol-producing facilities are possible in Uttar Pradesh and Tamil Nadu, and these could provide ethanol for an E10 blend, respectively, for Delhi and Chennai, the other two Indian cities to have the dubious distinction of being on the list of the world's 10 most polluted cities. The geographical distribution of this important crop for the entire country is shown in Figure 1 (USDA 1998).

Table 1. India's leading sugarcane-producing states

	1989-1990		1995-1996		1998-1999[a]	
State	**Production, Mt**	**% of Total**	**Production, Mt**	**% of Total**	**Production, Mt**	**% of Total**
Uttar Pradesh	97.0	44.6	109.9	43.1	NA	NA
Maharashtra	34.0	13.5	NA[b]	NA[b]	55.2	19.9
Tamil Nadu	21.9	11.2	13.1	12.3	NA[b]	NA[b]

[a]Estimates.
[b]Not available.

3.3 Sugar Industry in Maharashtra

Maharashtra State is a leader in both agriculture and industrial growth in India. As shown in Table 1, Maharashtra is the second largest sugarcane producing state in India. Typical sugar industry statistics for Maharashtra are shown below (REPSO 1998).

- Annual average cane production: 40–45 Mt
- Average sugar recovery: 11.11 Mt
- Number of sugar mills: 109 (cooperatives)

A comparison of Maharashtra state with the country as a whole, in terms of key industry parameters for the last 5 years, is presented in Table 2 (Maharashtra State Govt. 1998). Table 3 indicates that Maharashtra ranks second in India, based on the number of cane sugar mills (Maharashtra State Govt. 1998). However, in sugar production, it ranks first and surpasses even Uttar Pradesh, due to its high yield of sugar per t of cane. Since 1987, a minimum capacity of 2,500 t crushed per day (TPD) has been imposed for new mills, and incentives are in place to encourage expansion of existing mills to 5,000 TPD (Winrock International 1993). Maharashtra has 12 and 6 mills with crushing capacities of >3,500 TPD and >5,000 TPD, respectively.

The southern and western Maharashtra regions have a greater share of cooperative sugar factories in the state. Table 4 offers regional distribution of sugar factories in Maharashtra (Maharashtra State Govt. 1998).

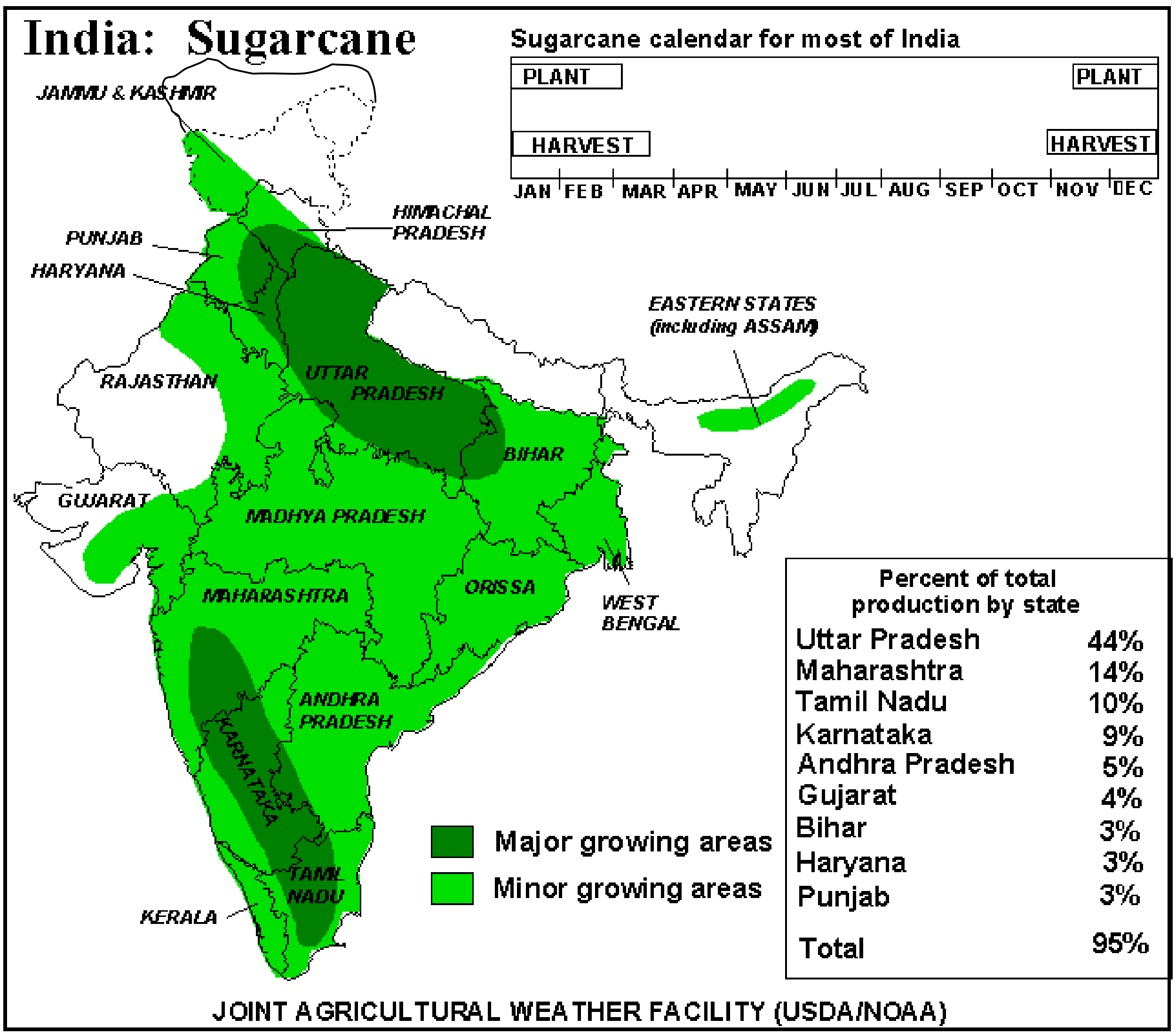

Figure 1. Geographical distribution of sugarcane production in India.

Table 2. Comparison of Maharashtra state and Indian national sugar statistics

	Maharashtra State[a]				India			
	1993-1994	1994-1995	1995-1996	1996-1997	1993-1994	1994-1995	1995-1996	1996-1997
Sugarcane cultivation, '000 ha	344 (10%)	519 (14%)	580 (14%)	516 (12%)	3422	3867	4147	4168
Yield, t/ha	81.1	85.5	80.4	81.0	67.1	71.3	67.8	66.5
Sugarcane production, Mt	27.89 (12%)	44.26 (16%)	46.65 (17%)	41.80 (15%)	229.66	275.54	281.10	277.25
Crushing capacity, Mt	24.68 (25%)	45.99 (31%)	51.47 (30%)	31.01 (24%)	98.33	147.64	174.72	130.38
No. of sugar mills	97 (25%)	107 (26%)	109 (26%)	105 (26%)	394	408	416	412
Average recovery, % cane	11.13	10.92	10.48	11.11	10.00	9.92	9.42	9.90
Sugar production, Mt	2.75 (28%)	5.02 (34%)	5.39 (33%)	3.44 (27%)	9.83	14.64	16.45	12.90

[a]% numbers in parentheses represent Maharashtra's contribution to the national statistics.

Table 3. Number of sugar mills in India by cane crushing capacity

State	TPD <1250	TPD 1250–2500	TPD 2500–3500	TPD 3500–5000	TPD >5000	Total Number of Mills
	Number of Mills at Specified Capacities					
Uttar Pradesh	36	13	43	7	12	111
Maharashtra	39	17	35	12	6	109
Andhra Pradesh	20	3	9	1	3	36
Tamil Nadu	5	6	19	2	2	34
Karnataka	13	3	7	4	4	31
Bihar	15	10	3	0	1	29
Gujarat	6	1	6	2	4	19
Punjab	5	2	11	1	0	19
Haryana	4	2	3	1	1	11

Table 4. Sugar factories in Maharashtra by geographical region

Geographical Region	Number of Sugar Factories	Installed Capacity, TPD
Total cooperatives	81	209,650
South and west	78	204,600
Central	27	51,250
Eastern	19	21,250

Table 5 lists data for Vasantdada Shetkari Sakhar Karkhana Ltd.'s (VSSK) sugar mill in Sangli, Maharashtra (Winrock International 1993; Smouse et al. 1998). The cane-crushing capacity at VSSK can be expanded to 7,500 TPD; however, mill management does not plan to expand beyond 6,000 TPD. This mill is considered as a typical candidate mill pertaining to ethanol production.

Table 5. Data for VSSK Ltd.'s sugar mill in Sangli, Maharashtra

Parameter	Value
Mill capacity, TPD	5000
Cane crushed, t/year	924,048
Crop duration, days/year	200
Average cane crushing rate, TPD	4,972
Downtime, % of milling season	19.4
Fiber, % of cane	13.7
Bagasse, % of cane	30.8
Moisture, % of bagasse	50.6
Bagasse produced, t	284,422

4 BIOETHANOL PRODUCTION IN MAHARASHTRA

Bagasse is the fibrous residue left after extraction of sugar from the cane and can be a good feedstock for bioethanol (i.e., biomass-derived ethanol) production. Bagasse is preferably used by the sugar mills for steam and power generation to satisfy internal needs; however, about 15%-25% of the bagasse is left after satisfying the mills' energy requirements, and this excess is not burned in the mill boilers. (Steam consumption in Indian sugar mills is as high as 50-55% on cane compared to 40% in Hawaii. With improvements in or replacement of existing boilers, the excess bagasse figure could be higher.)

A bagasse-based ethanol project is in the planning/development stage in the United States. BC International (BCI) is adapting a non-operational molasses-to-ethanol plant in Jennings, Louisiana, to process local agricultural residue (USDOE 1998). This is a first stand-alone, commercial, biomass-to-ethanol plant and is expected to produce about 75 million L/yr (20 million gal) of ethanol a year from sugarcane bagasse and rice hulls as feedstock. This project is proceeding toward commercialization, and being an industrial-scale demonstration of the biomass-to-ethanol technology, it can be used as a model for a plant in Maharashtra. Such an ethanol plant could be centrally located to utilize bagasse from several sugar mills within a 50-km radius.

4.1 Ethanol Capacity

Assuming that the typical sugar mill data in Table 5 apply, bagasse produced by a mill is about 285,000 t/yr. If 20% of the bagasse is excess, then each mill has an extra 57,000 t/yr. If three mills combine their excess bagasse, 171,000 t/yr of bagasse is available for ethanol (at 50% moisture, 85,500 t/yr of dry bagasse). This corresponds to a 23 million L/yr (ca. 6 million gal/yr) ethanol facility, which is fairly large by Indian standards. The annual petrol (gasoline) consumption in Mumbai is estimated to be 400–500 million L. Thus, the plant could supply about half of the ethanol demand, assuming that all gasoline is sold as E10 fuel—a blend of 90% gasoline and 10% ethanol by volume. If the other three large mills also contribute 20% of their bagasse, all the ethanol needed in Mumbai could be supplied by building a second plant, or a larger single plant.

Bagasse availability could be increased beyond the current levels via the following means (Rao 1997): 1) by introducing energy conservation measures in the sugar factories to reduce steam consumption, thereby reducing in-house bagasse usage, and 2) by substituting bagasse with other fuels in sugar factory boilers. One of the sugar factories in India is considering installing solar boilers. However, these measures are currently not in practice, and the increased bagasse availability is not assumed in this study.

An alternative feedstock that is available is cane trash, also known as cane residue or farm waste. For every 100 t of clean sugarcane, about 28 t of cane trash is left in the field and simply burned (Rao 1997). Based on this ratio, cane trash availability in Maharashtra alone can be estimated at approximately 16 Mt/yr (wet basis). However, the evaluation of cane trash for ethanol production is beyond the scope of this study.

4.2 Bagasse Storage

Crushing season for Maharashtra can be assumed as 200 days, running from October to May. Bagasse during the crushing season can be used as is, i.e., at 50% moisture. Whereas, for the rest of the 165 days, bagasse may need to be dried. Although bagasse drying with flue gases is an idea that is attractive in theory, it may not be feasible in India. Field experience in Hawaii has shown the potential for high maintenance and energy costs from parasitic power needed to operate the dryer and accessory equipment (Winrock International 1993). Solar drying is an attractive and potentially feasible option (Winrock International 1993, Rao 1997). Bagasse could be solar dried and stored before the onset of monsoon to last during the rainy season, which is finished by the beginning of the crushing season. A detailed discussion of this operation is beyond the scope of this analysis. An annual weighted-average moisture of 34% is used in process modeling.

5 LIFE CYCLE ASSESSMENT

5.1 Related Research

Biomass-derived ethanol has recently been the subject of life cycle analyses (NREL 1993, Wang et al. 1997, Wang et al. 1998). There has also been a series of studies estimating the life cycle energy balance of ethanol derived from corn (Morris and Ahmed 1992; Shapori et al. 1995). A recently completed study by Kadam et al. (1999) developed estimates of environmental flows, including air emissions, water effluents, solid waste, and the depletion of resources, associated with the disposal options for three types of biomass in California.

5.2 Study Objective

The objective of the current LCA study is to quantify and compare, over their life cycles, the comprehensive sets of flows to and from the environment (raw material and energy use, wastes, emissions, etc.) associated with the options of converting excess bagasse to ethanol versus discarding it as waste. Introduction of an E10 fuel blend (containing 10% bioethanol by volume) for motor vehicle use in Mumbai is compared with the gasoline currently being consumed. All of these flows are examined over the product life cycle, from production and extraction of raw materials through intermediate conversion processes, transportation, distribution, and use. Net life cycle energy consumption ("energy balance") is one component of the more comprehensive scope of an LCA such as undertaken in this study. Life cycle cost assessment is outside the scope of the current study.

5.3 Study Phases

The LCA study was divided into three phases as shown below; during each phase peer review was sought and comments were incorporated, when appropriate.

Phase I: Establish approach to LCA
Phase II: Develop database for LCA
Phase III: Conduct LCA
- Step 1: Develop LCA models
- Step 2: Generate final report

5.4 Life Cycle Assessment Principles

LCA is a technique for assessing the environmental aspects and potential impacts associated with a product, by:

- Compiling an inventory of relevant inputs and outputs of a system (life cycle inventory [LCI])
- Evaluating the potential environmental impacts associated with those inputs and outputs
- Interpreting the results of the inventory and impacts in relation to the objectives of the study.

LCA studies the environmental aspects and potential impacts throughout a product's life (i.e., from cradle to grave) from raw material acquisition through production, use, and disposal. The general principle for extending the system boundaries, to include various processes involved in producing and using a product, is illustrated in Figure 2, although the boundaries may not all be relevant to the LCA of a transportation fuel.

In the most straightforward and transparent approach to LCI interpretation, the inventory results may be used as-is to help identify and prioritize opportunities for pollution prevention or increases in material and energy efficiency for processes within the life cycle. A particular advantage of LCI applied in this way is its comprehensiveness. LCAs help detect the shifting of environmental burdens from one life cycle stage to another (e.g., lower energy consumption during use, achieved at the cost of much higher manufacturing energy consumption), or from one medium to another (e.g., lower air emissions at the cost of increased solid waste).

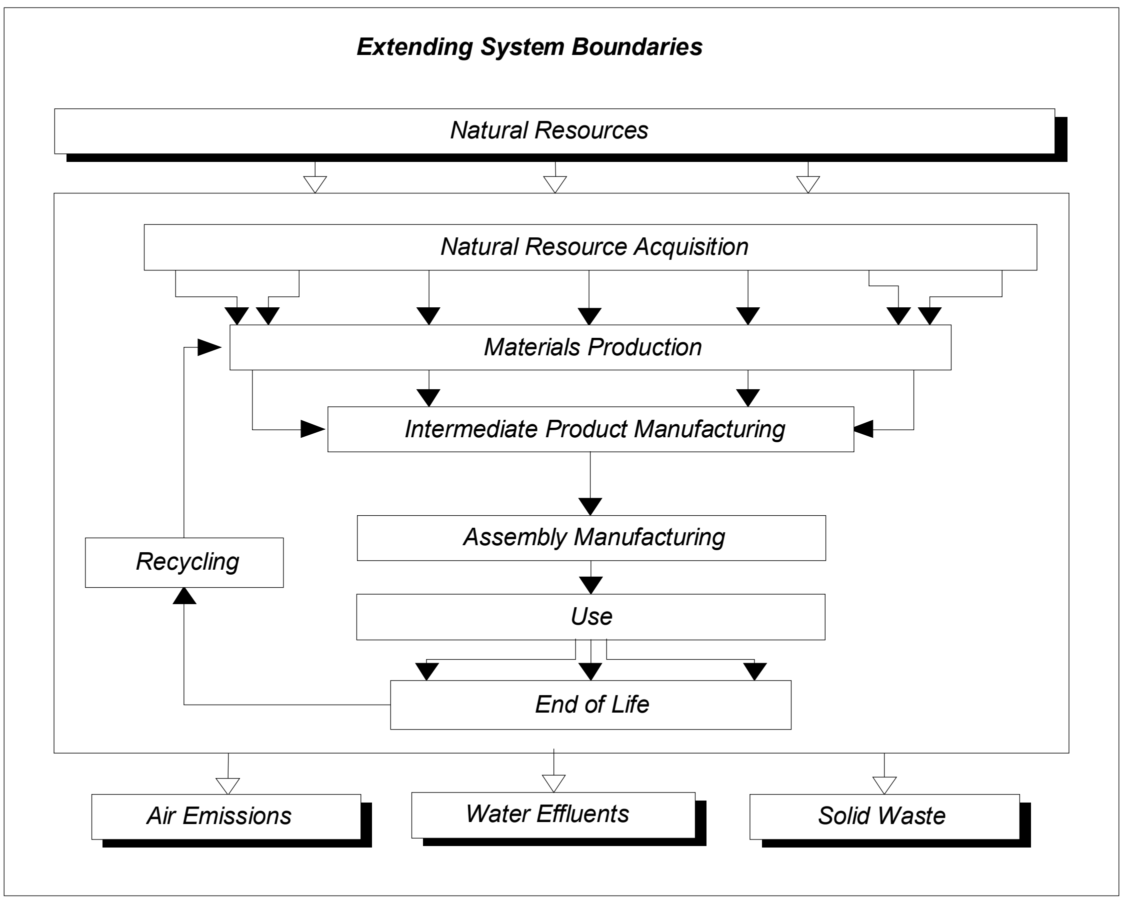

Figure 2. Schematic representation of extending system boundaries.

Because the number of flows calculated during an LCI analysis is often very large, subsets of the flows are sometimes consolidated or aggregated to facilitate interpretation, especially when two or more products or processes are being compared using LCA. This consolidation and aggregation of flows has been given the (perhaps misleading) name of life cycle impact assessment (LCIA). In fact, it is not the impacts of the environmental flows in the inventory that are estimated using LCIA. Instead, the inventory flows are consolidated and aggregated using information about their relative potential strength of influence on separate categories of potential environmental impacts, thereby generating indicators. The results within each LCIA impact category are useful for comparison of one product or process versus another, but have little meaning in an absolute sense (i.e., relative to estimating the actual environmental impacts of a product or process).

Because the results of an LCI and an LCIA are influenced by a significant number of assumptions and uncertainties, the interpretation phase usually includes some sensitivity analyses. This allows an assessment of the robustness of the baseline results, project assumptions, methodological choices, future scenarios, and uncertainties. In this study, data quality was assessed for its 1) precision, 2) completeness, 3) representativeness, 4) consistency, and 5) the origin of the data (measured, calculated, or estimated).

Principal aspects of LCI and LCIA are discussed briefly in the sections that follow. Further information about LCA methodology is provided in a number of publications from the Society of Environmental Toxicology and Chemistry (SETAC 1991; SETAC 1993a; SETAC 1993b; SETAC 1994), the U.S. Environmental Protection Agency (EPA) (EPA 1993a; EPA 1993b; EPA 1995a), the International Organization for Standardization (ISO 1996; ISO 1997), as well as other sources (Heijungs et al. 1992; SETAC–Europe 1992).

5.5 Methodology

5.5.1 Functional Unit

The comparison of different industrial systems can only be achieved if they perform the same function. Once this shared function is defined, a unit has to be chosen in order to compare the systems on the same quantitative basis. All the energy and mass flows in the inventory are normalized to this functional unit. Examples of how this is done are presented below.

- The comparison of different indoor paints (solvent-borne, water-borne, etc.) would be made on the following basis:
    - Function: covering a surface
    - Functional unit: the quantity of paint required to cover 5 m^2 of wall (this function could be further refined to take into account secondary functions like opacity, washability, durability and lifetime, etc.)
- The comparison of different gasolines could be made on the following basis:
    - Function: energy needed to travel 1 km
    - Functional unit: the quantity of gasoline or E10 fuel required to provide the necessary energy

5.5.2 Definition of System Boundaries

For each option being compared on a life-cycle basis, the corresponding systems are then determined (i.e., relevant processes to be included in the system are selected). The three main issues to address, for each of the systems, are discussed below.

1) Exhaustivity of the systems. The LCA theoretical principle implies that *each* material and constituent be studied and traced *back* to natural resources, and *forward* through final disposal. The strict application of this principle would lead to the study of almost every industrial process, because all industrial operations work within a complex network. In order to focus LCA projects on the main operations, quantitative rules are applied to exclude the constituents and ancillary materials whose impacts are estimated to be negligible compared to those of the overall studied system.
2) Identification of steps/operations that are different from one system to another. As the project focuses on a comparison, steps that are functionally equivalent for the compared products could be excluded from both systems. On the other hand, steps or operations that are not functionally equivalent for the compared products should be taken into account, i.e., included in the system boundaries.
3) Identification of coproducts and determination of the appropriate partitioning parameter. This facilitates proper allocation to a defined product its share of the total pollution, energy consumption, and material flows for which the process is responsible.

5.5.3 Interpretation: Life Cycle Impact Assessment

In this element of the LCA, after the inventory has been prepared, there are two further steps that need to be considered:

1) Whether and how to aggregate and/or consolidate the inventory data using information about each flow's relative potential strength of influence with respect to separate categories of potential environmental impact; and
2) Whether and how to aggregate the results of the step mentioned above, across the impact categories considered.

Note that the first of these two steps is pursued in addition to the LCIA, not as a replacement for it. Those attempting to develop a final "score" for comparing products or processes only use the second of these two aggregation steps. It was not used in this project because it requires value judgements (e.g., is water pollution more sinister than air pollution?), which are beyond the scope of this analysis.

6 SCOPING OPTIONS AND DECISIONS

This section presents the various parameters that should be considered in order to precisely define the scope of the project. These parameters can be addressed sequentially, as indicated in Figure 3. The process begins by first considering "project" level parameters that involve high-level choices that can have a profound impact on the general orientation and outcome of the project. These choices involve geographic, temporal, technical, and environmental aspects of the life cycle scenarios considered. Next, we need to consider more specific product parameters, including the exact nature and form of the products studied and the type of application in which they are used. The third group of parameters involves the production processes used to make the product. The types of choices made for high-level project parameters influence both product-and process-related parameters. Finally, there is a group of parameters that must be defined regarding the LCA methodology itself.

Subsequent sections address the separate scoping elements in turn, as follows:

Project Parameters	⇒	Section 6.1
Product Parameters	⇒	Section 6.2
Process Parameters	⇒	Section 6.3
LCA-Specific Parameters	⇒	Section 6.4

The key criteria that have been employed in selecting an option for each parameter are:

- Relevance to the project's goals
- Availability of data
- Time and cost constraints

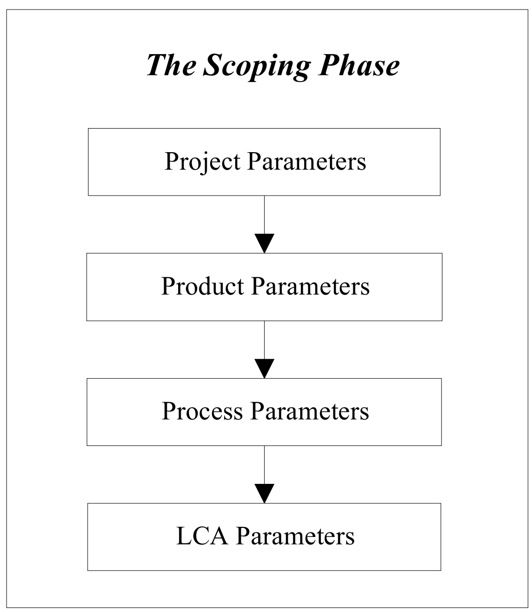

Figure 3. Elements of the scoping phase for life cycle analysis.

6.1 Project Parameters

6.1.1 General System Boundaries

Figure 4 shows the general system boundaries for the two scenarios considered in this study. In one scenario, bagasse is disposed of by burning (Scenario 1) and gasoline is used for transportation needs. In the alternative scenario, bagasse is converted into ethanol and used in reformulated gasoline (Scenario 2). Bagasse disposal by burning represents the *status quo*; this LCA compares bagasse conversion to ethanol with the *status quo*.

6.1.2 *Environmental Issues Considered*

The LCA methodology traditionally calls for complete mass and energy balances for each process, including energy consumption, raw material consumption, air emissions, water effluents, and solid waste. This comprehensive compilation exercise results in a quantification of all existing flows into the environment. However, this scheme has become increasingly questionable because of the following reasons.

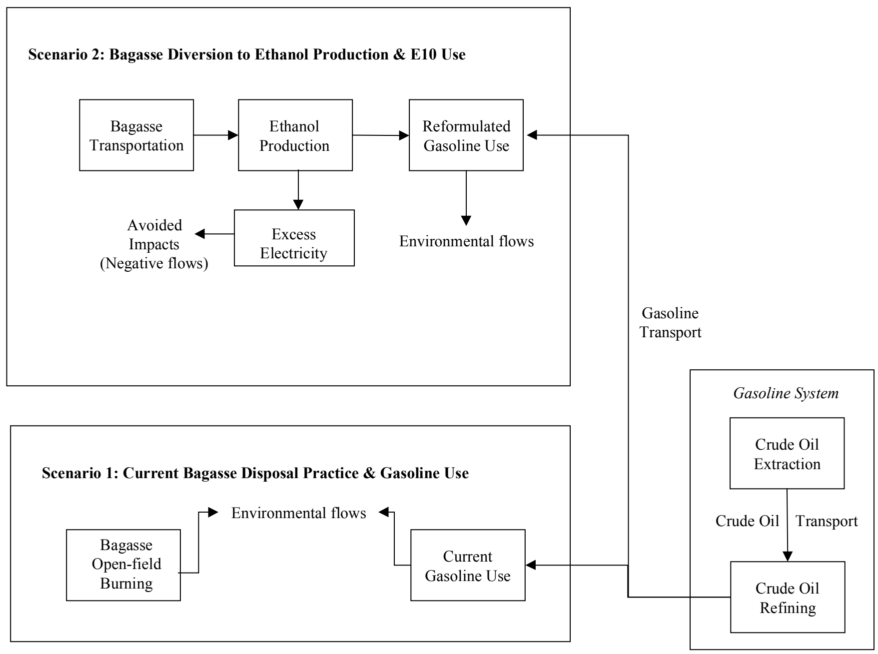

Figure 4. General system boundaries for the comparison of burning of excess bagasse versus its diversion to ethanol production.

- **Practical Reasons:** An ever-expanding number of parameters can be tracked within an inventory, reflecting more comprehensive data measurements. For instance, including U.S. Toxic Release Inventory (TRI) data would result in a list of approximately 200 pollutants being released during gasoline production. Similarly, including radionucleide emissions from electricity production would result in tracking more than 150 specific flows. Therefore, managing such a large inventory list adds to the complexity of carrying out as well as interpreting the LCA because these additional flows should be collected for all sources within the system for the sake of consistency.
- **More Fundamental Reasons:** By restricting the inventory data collection to the data actually needed in a subsequent decision analysis, a more focused LCA can be carried out, which ensures that the issues at stake receive the highest priority and data quality. Some studies even restrict their data collection to pollutants contributing to a single effect (e.g., greenhouse gases).

Therefore, it is important to understand the issues or impacts that are of greatest concern to the users (or decision-makers) of the LCA and then tailor the data collection to meet their needs. It should be noted that an inventory number (e.g., quantity of lead) is only an indication of a potential impact. Additional data such as ambient concentration, pathways to human and ecological toxicity, and the existence of thresholds would be needed to assess the actual impact of this emission. These additional data are of the type required in risk assessment in which exposure data are collected for a few emissions at a single site. An actual LCA would need to gather these additional data for all inventory flows and for all sites included in the system boundaries (generally well over a hundred). Because the limitations of inventories are well known, this type of actual impact assessment is as difficult as it is impractical.

LCA should consequently be considered as providing an indication of potential environmental impact, complementary to actual impacts evaluated by other tools. The following steps were used to facilitate interpretation of the inventory results through impact assessment.

- **Classification:** The organization of inventory data into environmental impact and resource consumption categories, such as global warming potential, acidification potential, eutrophication potential, natural resource depletion, etc.
- **Characterization:** Weighted summing of inventory data within each environmental impact category, based upon each flow's relative strength of potential influence upon the identified environmental impact or effect

The characterization step takes explicit account of the latest scientific assessments of the uncertainty inherent in the equivalency factors, such as global warming potentials. In addition, the discussion accompanying the characterization results clearly states that the results of a characterization analysis serve strictly to normalize the multiple flows within the LCI with respect to a particular environmental issue in terms of their relative strength of potential contribution to that issue. Characterization is not in any way intended to estimate the actual impact of the emissions upon environmental issues.

Furthermore, some of the inventory flows themselves may be highly uncertain, with an estimable magnitude of uncertainty. This uncertainty is appropriately combined with the uncertainty inherent in the equivalency factors used in the characterization step. Table 6 indicates the environmental inventory flows and their corresponding impact assessment categories considered in this study.

Some of these environmental flows can potentially have impacts on the environment that go beyond the effects caused by just the flow itself. For this study, the potential impacts of the life-cycle flows have been assessed for the following impact assessment indicators: greenhouse effect potential, natural resource depletion, acidification potential, eutrophication potential, human toxicity potential, air odor potential, and ozone-forming potential.

To calculate the impact indicators, each flow that is determined to be a contributor to one of these categories is weighted according to its impact in comparison to a set baseline, e.g., for the greenhouse effect potential indicator, the baseline is grams of CO_2 equivalent. The value for the flow is multiplied by this weighting factor to give an impact score for the particular flow. The impact scores for all contributing flows are then summed to give an overall impact score for potential impact. The weighting of the environmental flows is based upon the best available scientific knowledge; however, the score should be interpreted as potential impacts, not actual impacts. The exact methodology is discussed in more detail in Appendix B.

Table 6. Environmental inventory flows considered

Environmental Flow	Associated Impact Category
Natural Resources	
Oil	Natural resources depletion[1]
Coal	Natural resources depletion
Natural Gas	Natural resources depletion
Other significant resources depending on decision rules	Natural resources depletion
Water Effluents	
Chemical oxygen demand (COD)	Eutrophication potential
Biological oxygen demand (BOD)	Eutrophication potential
Nitrates	Eutrophication potential
Phosphates	Eutrophication potential
Total suspended solids	Direct use[a]
Metals	Direct use[a]
Air Emissions	
CO_2	Greenhouse effect potential
CH_4	Greenhouse effect potential
N_2O	Greenhouse effect potential
NO_x	Acidification potential
SO_x	Acidification potential
Particulate	Direct use[a]
Hydrocarbons	Ozone-forming potential
CO	Ozone-forming potential
Solid Waste	
Nonhazardous	Direct use[a]
Hazardous	Direct use[a]
Energy Use	
Total primary energy	Direct use[a]
Process energy	Direct use[a]
Fossil fuel energy	Direct use[a]

[a]Direct use: Not used in any impact assessment category.

6.1.3 *Geographical Scope*

The focus of the project is the use of excess bagasse in Maharashtra state and the use of E10 gasoline in Mumbai, Maharashtra. However, the geographic scope of particular data items

[1]Inflows such as sand, limestone, etc. could be used in the natural resources depletion index although their impact is negligible because of their abundance in nature.

pertains to whatever locations are dictated by actual plant locations, feedstock origins, sources of electricity, etc.

6.1.3.1 Gasoline System

In 1993, no unleaded gasoline was available in India. In that year, the 3.5 Mt of leaded gasoline used in India contained 0.56 grams of lead per liter (g Pb/L) (Earth Summit Watch 1995). The Government of India has adopted a program to introduce unleaded petrol in a phased manner. The plan proposes to reduce the maximum lead content in petrol to 0.15 g Pb/L. The Government is also undertaking a program for production of unleaded petrol at specific refineries, which could be supplied to Delhi and Mumbai in the initial phase.

The desirability of removing lead from gasoline is clear, and the EPA and the World Bank have discussed several aspects of this issue (EPA 1985; Lovei 1996; World Bank 1998). Supplying unleaded petrol throughout all of India may be possible with the commissioning of new refineries by 2005. India is one of the 10 countries that are the most likely candidates for phasing out the use of lead in gasoline by 2005 but that have not yet made firm decisions to do so (Earth Summit Watch 1999). Because there is no official commitment yet to adopt unleaded gasoline, leaded gasoline was assumed to be the "current gasoline" in this analysis.

The production and combustion of reformulated leaded gasoline, E10 fuel (10% ethanol and 90% leaded gasoline), was assumed to occur in Maharashtra. Currently, there is no biomass-derived ethanol being produced in India, and gasoline data from India is not readily available. Hence, surrogate data were used in the analysis. Leaded gasoline data was from Ecobalance Inc.'s database for European leaded gasoline production and use.

6.1.3.2 Ethanol System

The biomass used to make ethanol is of Maharashtra origin, and ethanol production is assumed to also occur in Maharashtra. However, for modeling purposes, U.S. average data are used. Data on ancillary materials needed for biomass to ethanol conversion was based on a U.S. average situation. The combustion of the E10 blend was assumed to follow an emissions profile based on Canadian Renewable Fuels Association data (CRFA 1999).

6.1.3.3 Electricity Production

Electricity production was based on Ecobalance Inc.'s data for India. This database was considered to be applicable to electricity production in Maharashtra.

6.1.4 Temporal Scope

The issue here is whether to study a current situation, or to model a future situation, or to model both current and future scenarios. Current and future scenarios could be quite different. For example, current scenarios would be limited to existing ethanol production technology as well as existing transportation vehicle scenarios and biomass availability scenarios.

One reason for studying a mid- to long-term time frame, is that a widespread use of biomass-derived ethanol in the very near term is not probable. However, the results of this study are data-driven, and the use of forecast or modeled (rather than current, empirically based) production, conversion, and end-use technology parameters would greatly increase the uncertainty in the final results. For this study, the middle part of the decade has been selected as the production period.

6.2 Product Parameters

6.2.1 Scenarios

Sugar mills generally use the boilers as incinerators to get rid of their bagasse. However, after satisfying their energy needs, the leftover bagasse is essentially a waste stream. Excess bagasse, which is 15%-25% of the total generated, is usually burned on the land, i.e., open-field burned (Wayman and Parekh 1990). All the three Indian mills in the USAID study considered excess bagasse as a problem (Winrock International 1993), and they currently operate under conditions where excess bagasse causes operational problems of storage and handling with no economic benefits as an energy source. Also, the same study mentions decomposing as a current alternative for bagasse disposal. Hence, it is reasonable to set decomposition or open-field burning as an existing scenario representing the *status quo*; the latter is used as the existing disposal mode in this study. Diversion of excess bagasse to ethanol production represents the alternative scenario.

6.2.2 Functional Unit

The functional unit of this study is the disposal of a defined amount of bagasse, i.e., 1 dry t. Bagasse-derived ethanol is used in reformulated gasoline (E10), which replaces current gasoline on an energy-equivalent basis. The equivalency between current gasoline and E10 blend is explained in Table 7. The environmental burdens are calculated on a differential basis in the case of gasoline. This approach is explained in section 5.5.2 on Definition of System Boundaries. The gasoline burdens of both the scenarios are reduced by the amount of gasoline required in the ethanol scenario. This is further illustrated in
Figure 5.

Table 7. Equivalency between current gasoline and E10 blend

	Current Gasoline	E10 Blend
Heating value, MJ/L	31.1	30.1
Oxygen content, wt %	0	3.50
Density, kg/L	0.750	0.754
Weight fraction ethanol	0	0.105
Weight fraction gasoline	1	0.895
Volume to achieve 31.1 MJ, L	1.000	1.035
Total fuel, kg	0.750	0.780
Gasoline, kg	0.750	0.698
Ethanol, kg	0.000	0.082
Equivalency:	1 kg ethanol + 8.555 kg gasoline (9.555 kg E10 blend) equivalent to: 9.188 kg current gasoline	
On a differential basis:	1 kg ethanol equivalent to: 0.633 kg current gasoline	

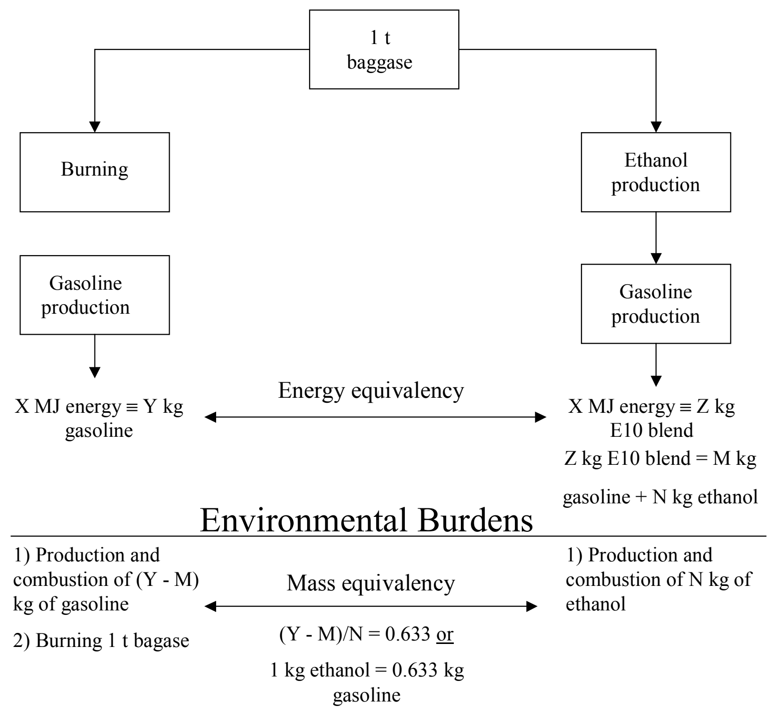

Figure 5. Energy and mass equivalency between current and future scenarios in the context of the functional unit.

6.3 Process Parameters

Process parameters are strongly affected by the choices made on the project-related and product-related parameters. For example, the assumption of using technology based on the middle part of the decade for all processes leads to a number of conclusions about fuel production and feedstock supplies.

Feedstock for gasoline is crude oil produced domestically and imported from foreign countries. Data characterizing the split between foreign and domestic crude oil supplies to fuel production were used, with regional differences taken into account. Given that the data were from the United States or Europe, “domestic” refers to these locations.

For the ethanol scenario, two ethanol production processes were evaluated: an enzyme-based process and a dilute-acid-based process. BC International is adapting an existing (non-operational) molasses-to-ethanol plant in Jennings, Louisiana to process local agricultural residues using a dilute-acid process. The dilute-acid process can be a near-term option because it does not involve enzyme production, which is considered a longer-term process at this juncture.

6.4 LCA-Specific Parameters

6.4.1 Allocation Rules

The production of both fuel ethanol and gasoline generates other products, which are recovered and used in other product systems. They are considered coproducts. The problem is the apportioning or allocating of energy resources, raw materials, pollutants, etc. from the common production steps to the product studied (fuels) and the coproducts. Inputs and outputs of the common steps can be partitioned across the coproducts on various bases, including (for example):

- Mass
- Dry mass
- Energy content

For this analysis, there were two main processes that required allocation. Crude oil refining produces a number of petroleum products. This study was mainly interested in one of those products, namely gasoline. Allocation of the refinery energy use and emissions was done on an energy basis. Another process that required allocation was ethanol production. The production of ethanol also produces lignin as a coproduct, which can be used as an energy source. The allocation technique used in the study was to expand the system boundaries to include the use of the lignin residue for on-site cogeneration. In this way the emissions from an alternate energy production method were offset by the use of the lignin. These offset emissions were accounted for as negative values in the life cycle.

6.4.1.1 Modeling Biomass-Based CO_2 Emissions

The carbon in the biomass portion of the ethanol is derived from the CO_2 absorbed by plants during photosynthesis. These carbon atoms are released at the end of the products' life, predominantly in the form of CO_2, but also in the form of CO, hydrocarbons or methane (CH_4) molecules. These carbon releases are offset (though not all at the same rate) by the CO_2 uptake or sequestering during plant growth. A distinction was made between net carbon emissions from the production and subsequent combustion of biomass products and carbon emissions from the combustion of fossil fuels. The carbon uptake by plants was accounted for as a credit. Only fossil CO_2 is used in estimating greenhouse potential.

6.5 Summary of Scoping Decisions and Approaches

Table 8 summarizes the scoping decisions and approaches used in this project, which were described in the previous sections 6.1 through 6.4.

Table 8. Summary of scoping decisions and approaches

Element	Parameter Type	Decision or Approach
Project	Spatial	Biomass: Maharashtra Fuel production: Worldwide Fuel use: Maharashtra
	Temporal	2005
Product	Biomass	Bagasse
	Current disposal alternative	Burning
	Functional Unit	Conversion of 1 dry t of bagasse to ethanol
Process	Ethanol	Bioconversion technology: 1) dilute acid pretreatment, followed by enzyme hydrolysis/fermentation or 2) two-stage dilute acid hydrolysis followed by fermentation
	Gasoline	Feedstock: domestic plus imported crude oil Refining: 2005
	Electricity	Electricity production for India (average)
LCA	Coproduct allocation	Energy based for petroleum products Expansion of system boundaries to include lignin residue use for on-site cogeneration
	Interpretation	Classification and characterization Perform sensitivity analysis, if necessary, on uncertain or variable input parameters

7 LIFE CYCLE MODELING

7.1 LCA Software

The TEAM™ software (version 3.0) developed by Ecobalance Inc. (Bethesda, Maryland) was used in this analysis.

7.2 General Bagasse Data

Proximate chemical compositions, of both unbaled and commercially baled, bagasse produced in Florida, Hawaii, and Louisiana are given in Table 9 and Table 10. This data collected by Atchison (1993) is old but still useful.

The calorific value and the elementary analysis for bagasse are shown in Table 11. Recent data on bagasse composition, both from the literature (Johnson et al. 1992) and this study (based on NREL laboratory analysis), are provided in Table 12. Both sets of data agree quite well with each other. Johnson et al. (1992) also studied the changes in bagasse composition due to storage; their data, shown in Table 13, does not predict significant sugar loss. In this analysis no change in bagasse composition upon storage is assumed.

Table 9. Proximate chemical composition of bagasse produced in Florida and Hawaii (oven-dry basis)

Variety	Source	Crop Year	Ash %	Lignin %	Pentosans[a] %	Solubility in: Hot Water %	Solubility in: Alcohol Benzene %	Solubility in: 1% NaOH %	Cross & Bevan Cellulose %	Alpha-cellulose[b] %
Florida										
-	Clewiston	1948	2.2	18.1	27.9	11.2	10.8	39.9	52.0	33.7
CI.41-223	Clewiston	1952	1.0	18.2	26.6	15.1	7.0	40.7	48.0	30.6
F.31-436	Clewiston	1952	1.6	16.4	27.4	15.5	6.4	43.2	48.8	30.8
F.31-962	Clewiston	1952	2.2	18.6	28.7	9.8	8.0	40.0	49.0	31.5
Mean			1.8	17.8	27.6	12.9	8.0	41.0	49.4	31.6
Hawaii										
8560		1952	5.4	21.3	27.7	5.7	3.2	33.9	50.2	31.8
-	Laupahoehoe	-	1.9	22.5	31.2	3.4	2.1	31.4	55.4	34.3
1933	Ewa	-	2.6	19.3	31.3	4.0	3.6	31.3	55.0	31.6
1933	Oahu	-	3.3	20.1	31.0	2.7	3.4	32.0	52.0	31.7
Mean			3.3	20.8	30.3	4.0	3.1	32.2	53.2	32.4

[a]Pentosans = furfural x factor 0.8.
[b]Corrected for pentosans and ash, basis original material.
Source: "Pulp & Paper Prospects in Latin America," pp. 294-314, United Nations, NY, 1955; and USDA Mimeo Circ. ARS-71-4, March 1955.

Table 10. Proximate chemical composition of commercially baled sugarcane bagasse (oven-dry basis)

Source & Condition	Crop Year	Ash %	Solubility in Alcohol Benzene %	Solubility in Hot Water %	Solubility in 1% NaOH %	Lignin %	Pentosans %	Cross & Bevan Cellulose %	Alpha-Cellulose %
Lockport, LA, Baled, stored 9 months	1941	2.9	1.7	4.0	32.9	21.3	29.4	58.4	36.8
Stored	1937	1.8	1.7	-	-	26.6	29.1	60.2	43.1
Stored	1940	6.3	4.0	9.1	36.1	19.6	28.4	55.0	40.6
Houma, LA, dried immediately, baled, represents fresh bagasse	1941	2.4	6.0	8.1	35.9	18.9	30.0	53.3	33.4
Clewiston, FL, freshly dried, dry-screened	1948	2.2	3.5	11.2	39.9	18.1	28.5	52.0	33.7

Source: "Pulp & Paper Prospects in Latin America," p. 256, United Nations, 1955; and data published by the USDA Northern Regional Research Laboratory, Peoria, IL.

Table 11. Calorific value and the elemental analysis for bagasse

Parameter	Value (dry basis)
Calorific value	18,950 kJ/kg
Carbon	47.0%
Hydrogen	5.5%
Nitrogen	1.7%
Sulfur	0.1%
Oxygen (by difference)	45.7%

Table 12. Recent data on bagasse composition

Feedstock Component	Johnson et al. (1992) Dry wt %	Current Study–Hawaiian Bagasse Dry wt %
Glucan	41.0	40.6
Galactan	0.5	0.8
Mannan	0.4	0.2
Xylan	23.2	20.0
Arabinan	2.2	1.7
Lignin	24.3	25.5
Extractives	3.8	1.8
Ash	2.6	3.7
Uronic acids	2.3	5.7
Total	100.3	100.0

Table 13. Changes in bagasse composition due to storage

Components	Composition[a]	% Change Compared to Day Zero[b]		
	Day Zero	*Pile Center*	*Crust*	*Compost*
Extractives[c]	3.8±0.1	-2.1	<2	+9.2
Ash[c]	2.6±0.1	<0.2	+2.1	+3.5
Composition Data on an Extractives-free Basis				
Total Lignin[d]	24.3±0.3	+0.5	+0.8	+8.6
Uronic Acids	2.3±0.7	<1.1	<1.1	-1.4
Arabinan	2.2±0.1	-0.5	-0.5	-0.8
Xylan	23.2±0.4	+0.6	-1.9	-10.6
Mannan	0.4±0.1	<0.1	+0.1	<0.1
Galactan	0.5±0.03	<0.1	<0.1	-0.2
Glucan	41.0±1.0	+3.0	-2.1	-3.0
Mass Closure[a]	96.6±1.2	98.8	95.4	94.2

[a]Wt % on an oven-dried basis.
[b]Significant at the 95% confidence level.
[c]Contents determined on a whole biomass basis for the -20/+80 mesh fraction.
[d]Total lignin and other insoluble materials including condensed proteins, but not ash.

7.3 Bagasse Burning

As mentioned earlier, the standard disposal option for bagasse was determined to be burning, which represents the *status quo*. Because no data were available for bagasse burning, a surrogate data set was used. The air emissions were calculated using emission factors provided by the EPA (EPA 1995b) for biomass burning. Sulfur dioxide and carbon dioxide emissions for each scenario were based on the estimated sulfur and carbon contents, respectively, of green feedstock and ligneous residues. The reason for deviating from the EPA data for sulfur dioxide emissions is the relatively high sulfur content of bagasse.

7.4 Ethanol Production

Ethanol production from corn or molasses is a well-established technology with several plants located in the Midwestern United States and Brazil. Using lignocellulosic biomass as a substrate to make ethanol is also a promising approach. Many sources of lignocellulosic biomass, such as agricultural residues, forestry residues, pulp and paper waste streams, and municipal solid waste, are abundant and underutilized resources, which can be converted to ethanol.

The production of ethanol from biomass requires the following basic steps: pretreatment to hydrolyze the hemicellulose, hydrolysis of cellulose to produce glucose, fermentation of sugars to ethanol, and ethanol recovery. There are different process configurations, both enzyme based and nonenzyme based, that can be used to achieve the overall goal. In the nonenzyme based approach, acid is used for both hemicellulose and cellulose hydrolysis, and the mode is separate hydrolysis and fermentation (SHF); both six-carbon (hexoses, i.e., glucose, mannose, and galactose) and five-carbon sugars (pentoses, i.e., xylose and arabinose) are fermented to ethanol. In the enzymatic approach, dilute-acid pretreatment is used to hydrolyze the hemicellulose portion. The saccharification (hydrolysis) of cellulose to cellobiose and eventually to glucose is catalyzed by the synergistic action of cellulase and β-glucosidase enzymes. The mode of operation used is simultaneous saccharification and cofermentation (SSCF); cofermentation refers to the fermentation of both six-carbon and five-carbon sugars to ethanol. In this study the following two specific biomass-to-ethanol conversion technologies are used:

- Enzyme-based process
- Two-stage dilute-acid process

The flow diagrams for the two technology options are shown in Figure 6 and Figure 7, and process descriptions follow. It is assumed that no corn steep liquor (CSL) is used in fermentations because CSL is not relevant to a plant in India. (CSL is used in the processes described by Kadam et al. 1999.) Instead, an equivalent amount of ammonia, based on nitrogen content, is used; no other nutrients or micronutrients are added (or if necessary, are assumed to be available in the hydrolysis milieu).

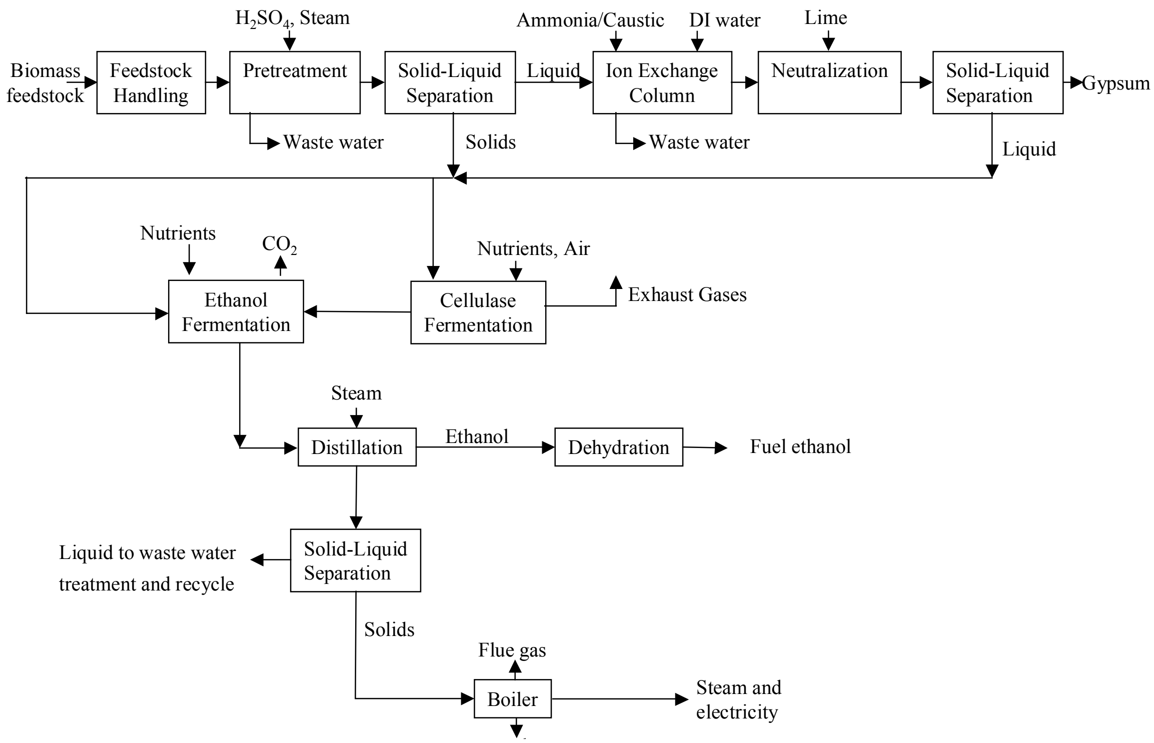

Figure 6. Enzymatic process flow diagram.

7.4.1 Enzymatic Process

A generalized process was modeled based on *Trichoderma reesei*-derived cellulases for cellulose hydrolysis and an appropriate recombinant ethanologen for cofermentation of six-carbon and five-carbon sugars to ethanol. The enzyme-based process, which is a relatively long-term option, consists of four basic unit operations:

1) Pretreatment
2) Cellulase production
3) Ethanol production
4) Product purification

7.4.1.1 Feedstock Preparation and Pretreatment

The biomass is milled to an average size of 15 mm. A screw feeder conveys the biomass from the storage bunker to the acid impregnator. Dilute sulfuric acid and low-pressure steam are also fed to the acid impregnator. The acidic slurry is discharged from the acid impregnator into the pretreatment reactor. High-pressure steam and additional dilute sulfuric acid are fed to the reactor where hemicellulosic sugars are hydrolyzed to their respective monomers and/or oligomers (temperature ranges from 160°–180°C, liquid phase acid concentration ranges from 0.7%–1.0% wt.).

The hydrolyzed mash is discharged from the acid hydrolysis reactor into a lower-pressure flash drum where cooling quenches the reactions. The hydrolyzate is separated from the solids in a solid-liquid separation step. The hydrolyzate is then pumped to the neutralization and detoxification tank using continuous ion exchange that employs a weak-base anion resin. The process primarily removes acetic acid and other organic species that could be toxic to the microorganisms used during fermentation.

Lime is used to neutralize the detoxified hydrolyzate; the neutralization reaction produces calcium sulfate, which is removed in a solid-liquid separation step. The neutralized hydrolyzate is pumped through a heat exchanger where, using cooling tower water, it is cooled to fermentation temperature. The hydrolyzate and solids from the solid-liquid separation step are then pumped to the ethanol fermentation section.

7.4.1.2 Cellulase Production

Cellulase production is by *T. reesei* using a slipstream of pretreated biomass as a carbon source. The fermentation is conducted in fed-batch mode at 28°C and pH 5. For a low-cost product such as ethanol, the enzyme need not be processed to any great extent to be useful. Whole broth from cellulase fermentation is actually more effective for the SSCF process. In this process, the whole fermentation broth is used as a source of cellulase enzyme. Because enzyme production is via the fed-batch mode and the SSCF is a continuous process, a surge storage tank is necessary. It is assumed that cellulase production using pretreated bagasse as substrate is feasible.

7.4.1.3 Fermentation

The SSCF process using cellulase enzymes and a recombinant *Zymomonas mobilis* converts cellulose and five-carbon sugars to ethanol and CO_2. Cellulase catalyzes the hydrolysis of cellulose to glucose. A recombinant xylose-fermenting yeast, recombinant *E. coli* and *Klebsiella oxytoca* are also possible choices.

The SSCF operation takes place in continuous anaerobic fermenters. Gravity drives the flow of fermentation broth between fermenters. Fermentation exhaust gases consisting of carbon dioxide and ethanol vapor are sent to the vent scrubber for ethanol recovery. The SSCF broth is pumped to the distillation section.

7.4.1.4 Distillation and Ethanol Dehydration

Ethanol is separated from the fermentation beer by conventional distillation technology and is dehydrated using molecular sieve technology. The still bottoms are collected and the 99.7% ethanol is sent to fuel storage. The lignin residue is further dewatered in a solid-liquid separation step. The liquid stream is sent to wastewater treatment and the recycle loop.

7.4.1.5 Ligneous Residue

The dewatered ligneous residue is burned on-site to cogenerate steam and electricity that can be used by the process. Excess electricity is generated, which can be sold to the grid.

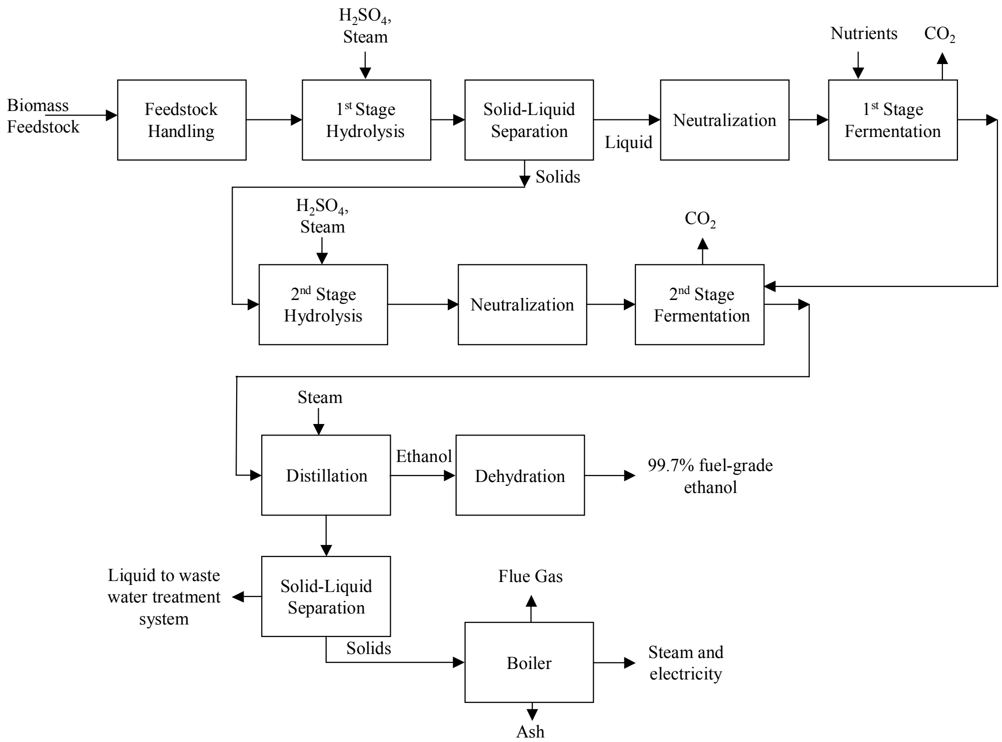

Figure 7: Two-stage dilute-acid process flow diagram.

7.4.2 Two-Stage Dilute Acid Process

The two-stage dilute acid process, which is a short-term option appropriate for a plant in India, consists of four basic unit operations:

1) First stage hydrolysis
2) Second stage hydrolysis
3) Ethanol fermentation
4) Product purification

7.4.2.1 First-Stage Hydrolysis

Prior to acid hydrolysis, the biomass is milled to an average size of 15 mm. The feedstock is then mixed with dilute sulfuric acid at a concentration of 0.70% and soaked at 50°C for 3 hours. In the first hydrolysis, the acid-impregnated biomass is heated to 180°–185°C for 3-5 minutes in a digester (hydrolyzer) to hydrolyze the hemicellulose; some cellulose hydrolysis also takes place in this step. The resulting slurry is pressed to obtain a liquid stream, which is sent to neutralization. Residual acid in the sugar stream is neutralized by adding lime, which forms a gypsum precipitate. Gypsum is removed in a solid-liquid separation step. The liquid stream is sent to first-stage fermentation.

7.4.2.2 Second-Stage Hydrolysis

The solids remaining after the first hydrolysis and solid-liquid separation are again acid-impregnated at the same conditions. In the second hydrolysis step, acid-impregnated material is heated for 3-5 minutes at 200°–210°C to effect further cellulose hydrolysis. The resulting slurry is neutralized by adding lime. This stream is sent to second-stage fermentation without separating out the gypsum.

7.4.2.3 Fermentation

A recombinant *Z. mobilis* is used to ferment both six-carbon and five-carbon sugars to ethanol and CO_2. (A recombinant xylose-fermenting yeast, rDNA *E. coli* or *K. oxytoca* can also be used.) First- and second-stage fermentations are carried out in continuous, anaerobic fermenters. The flow of fermentation broth between fermenters is facilitated by gravity. Fermentation off gases, containing mostly CO_2 and ethanol vapor, are sent to the vent scrubber for ethanol recovery. The fermentation broth is sent to the distillation section.

7.4.2.4 Distillation and Ethanol Dehydration

Ethanol is separated from the fermentation beer by conventional distillation technology and is dehydrated with molecular sieve technology. The 99.7% ethanol is sent to fuel storage. The lignin residue is further dewatered in a solid-liquid separation step. The liquid stream is sent to wastewater treatment and the recycle loop.

7.4.2.5 Ligneous Residue

The dewatered ligneous residue, containing mostly lignin and cellulose, is burned on-site to cogenerate steam and electricity that can be used by the process. The net electricity produced is sold to the grid.

7.4.3 Data Summary for Bagasse-to-Ethanol Processes

The estimates of inputs and outputs for the two processes were developed using NREL's Aspen®-based (Aspen Technology, Inc., Cambridge, MA) models, with technology targets established for the middle of the decade (Wooley et al. 1999). These estimates, using 1 kg of dry bagasse or 1 L of ethanol as the basis, are reported in Table 14. Combustion-related properties of green feedstock and ligneous residues are listed in Table 15. These are useful in calculating energy, CO_2, and ash generation.

7.5 Sulfuric Acid Production

The production of sulfuric acid (H_2SO_4) was modeled based on the contact process according to the following reactions:

$$2\ SO_2 + O_2 \rightarrow 2\ SO_3$$
$$SO_3 + H_2O \rightarrow H_2SO_4$$

Emissions information is based on data collected from a number of production plants worldwide, as well as engineering calculations.

Table 14. Data summary for bagasse-to-ethanol processes

Environmental Flows	Enzymatic Process		Two-Stage Dilute Acid Process	
Inputs	(kg/kg bagasse)	(kg/L ethanol)	(kg/kg bagasse)	(kg/L ethanol)
Biomass	1.000	3.318	1.000	4.242
Lime	0.009	0.030	0.013	0.057
Water	1.966	6.525	3.591	15.232
NH_3	0.028	0.093	0.025	0.106
Diesel	0.005	0.017	0.004	0.019
H_2SO_4	0.044	0.146	0.048	0.202
Outputs	(kg/kg bagasse)	(kg/L ethanol)	(kg/kg bagasse)	(kg/L ethanol)
Ethanol	0.238	0.789	0.186	0.789
Gypsum	0.025	0.083	0.031	0.132
Ash	0.040	0.132	0.077	0.328
Ligneous residue	0.444	1.472	0.600	2.542
Biogas methane	0.015	0.051	0.016	0.070
Total CO_2	1.170	3.883	1.307	5.545
	(MJ/kg biomass)	(MJ/L ethanol)	(MJ/kg biomass)	(MJ/L ethanol)
Net electricity	0.859	2.849	1.146	4.863

Table 15. Combustion-related properties of green feedstock and ligneous residues

	Green Feedstock	Enzyme Process Fuel Residue	Acid Process Fuel Residue
Average heating value, MJ/kg	19.29	21.54	19.22
Carbon content, dry wt %	48.76	57.91	52.74
Ash content, dry wt %	3.70	8.21	11.63

7.6 Ammonia Production

Synthetic anhydrous ammonia production was modeled based on the natural gas-reforming process. Natural gas is used both as feedstock and fuel in this process at the following levels:

- 60% feedstock (the feedstock value of the ammonia = 23.61 MJ)
- 40% fuel

The process modeled assumes no CO_2 recovery.

7.7 Lime Production

The process model for lime production includes: limestone extraction, limestone crushing, and limestone calcination. The production of lime was modeled according to the following reactions:

$CaCO_3$	$\rightarrow$	$CaO + CO_2$		
100		56	44	(g/mole)

Transport of limestone to a user facility is not taken into account because its impact is negligible.

7.8 Electricity Production

The electricity grid model includes the following:

- Precombustion processes: coal mining (surface and underground) and transportation, natural gas extraction and transportation, crude oil extraction (off-shore and on-shore) refining, and transportation, production of nuclear fuel (UF_6 accumulation and fuel rod manufacturing), and hydroelectric power production
- Combustion in power plants
- Distribution (losses: 7.7%)

An average situation for India modeled by Ecobalance Inc. was used.

7.9 Steam Production

The energy necessary to convert water to steam is based on the enthalpy of the steam (2.6 MJ/kg at approximately 150 psi and 350°F) and a boiler efficiency of 80%. Steam is assumed to be produced by combusting fuel in industrial boilers. The fuel can consist of coal, natural gas, heavy fuel oil, or ligneous residue (from ethanol fermentation). The heating values for ligneous residues are given Table 15; those for the other fuels are as follows:

- Natural Gas – 52 MJ/kg
- Heavy Fuel Oil – 42 MJ/kg
- Coal – 29.3 MJ/kg

The emission factors for industrial boilers were obtained from the AP-42 report by the EPA (EPA 1995b). These numbers were compared with a study done by the Argonne National Laboratory (Wang 1996), to verify and expand on the EPA emission factors.

All the factors reported are for uncontrolled emissions. If control technologies are used, the emission factors should be reduced by the efficiencies of the control devices. Emission factors for heavy fuel oil and natural gas production are outlined by Kadam et al. (1999).

7.10 Gasoline System

This system includes precombustion data for gasoline. The precombustion steps include extraction of crude oil from the ground, transportation of the crude oil to a refinery, and refining the crude oil into finished refinery products. Transportation of the finished refinery products to the point of use is also included at this stage.

7.11 Gasoline and E10 Fuel Combustion

The modeling of gasoline combustion is based on emissions from E10 (oxygenated gasoline) and current gasoline.

7.11.1 Tailpipe Emissions

Toxic air pollutants can be emitted from motor vehicle systems by two emission-producing processes: combustion products from the exhaust system and evaporation from the fuel storage and delivery system. An overall emissions profile from the exhaust system and evaporation is given in Table 16 for the current gasoline and E10 blend. Overall emissions for the current leaded gasoline are from Ecobalance Inc.'s database for European leaded gasoline, and those for the E10 blend were estimated by incorporating the change in emissions discussed in Table 17 for low-level ethanol blends, such as E10 (CRFA 1999). For example, a 20% reduction in CO (lower than that in Table 16) for the E10 blend yields 158 g CO per kg fuel (198 x 0.8). Components specific only to gasoline combustion, e.g., benzene were reduced by 10% for the E10 blend. Although some data are available for emissions of ethanol blends (Harvey and Adler 1988; Taylor et al. 1996; CARB 1998), these are for very specific cases, and the estimates generated in Table 16 were considered to be generally more applicable.

Table 16. Overall emissions for current gasoline and E10 blend

	Current Gasoline, g/kg	E10 Blend, g/kg
Benzene	1.53	1.37
Benzo(a)pyrene	$5x10^{-5}$	$4.5x10^{-5}$
Carbon dioxide	2775	2784 (2583.6 fossil + 200.8 biomass)
Carbon monoxide	198	158
Ethanol	0	0.38
Hydrocarbons (except methane)	38	37.5
Lead	0.2	0.18
Methane	1.5	1.34
Nitrogen oxides (NO_x as NO_2)	31	32.6
Nitrous oxide (N_2O)	0.13	0.13
Sulfur oxides (SO_x as SO_2)	0.26	0.23

Table 17. Overview of change in emissions from low-level and high-level ethanol blends

Emission	Low-Level Blends (e.g., E10)	High-Level Blends (e.g., E85)
Carbon monoxide (CO)	25-30% decrease	25-30% decrease
Carbon dioxide (CO_2)	10% decrease	Up to 100% decrease (E100)
Nitrogen oxides (NO_x)	5% increase or decrease	Up to 20% decrease
Volatile organic compounds (VOCs)		
Exhaust	7% decrease	30% or more decrease
Evaporative	No change (in Canada)	Decrease
Sulfur dioxide (SO_2) and Particulate matter	Decrease	Significant decrease
Aldehydes	30-50% increase (but negligible due to catalytic converter)	Insufficient data
Aromatics (benzene and butadiene)	Decrease	More than 50% decrease

Unlike in the United States, where ethanol blends have a regulatory waiver (in most parts of the country) and are allowed to have increased volatility, Canadian regulations require that the volatility of ethanol blends must match that of standard gasoline (CRFA 1999). Hence, the evaporative emissions of VOCs from ethanol blends in Canada are approximately equal to those from conventional gasoline. It is assumed that the Canadian regulatory model is followed in India.

Because the environmental burdens are calculated on a differential basis, i.e., 1 kg ethanol in Scenario 2 versus 0.633 kg gasoline in Scenario 1, combustion emissions of Scenario 2 were modified as discussed here. Emissions that were solely from gasoline were omitted from those for ethanol. Those that were common emissions were apportioned to gasoline and ethanol-based on their carbon contribution to the blend. Ethanol's contribution to these emissions was then 6.4% of the total blend. This was then expressed based on a unit kg of ethanol (Table 18). This approach was considered to be better for a fair comparison of the two scenarios.

7.11.2 Biomass versus Fossil Fuel CO_2

A portion of the CO_2 that is generated from the combustion of the oxygenated fuel containing ethanol comes from biomass. The amount of biomass-derived CO_2 was calculated based on the carbon content of ethanol. CO_2 sequestered in the biomass is carried through the LCA as CO_2 (biomass) versus CO_2 (fossil), which results from the combustion of petroleum resources. Biomass and fossil CO_2 were treated individually in the LCA model and reported separately in the results.

Table 18. Apportioned emissions for E10 Blend

	Current Gasoline, g/kg	E10 Blend, g/kg	Apportioned Emissions E10 Blend, g/kg blend		Ethanol contribution, g/kg ethanol
			Gasoline	Ethanol	
Benzene	1.53	1.37	1.37	0.00	0.00
Benzo(a)pyrene	5.00E-05	4.50E-05	4.50E-05	0.00	0.00
Carbon dioxide, biomass	0	200.2	0.00	200.2	1913.0
Carbon dioxide, fossil	2775	2584	2584.0	0.00	0.00
Carbon monoxide	198	158	148.0	10.03	95.9
Ethanol	0	0.38	0.00	0.38	3.63
Hydrocarbons (except CH_4)	38	37.5	35.12	2.38	22.8
Lead	0.2	0.18	0.18	0.00	0.00
Methane	1.5	1.34	1.25	0.09	0.81
Nitrogen oxides (NO_x as NO_2)	31	32.6	30.53	2.07	19.8
Nitrous oxide (N_2O)	0.13	0.13	0.12	0.01	0.08
Sulfur oxides (SO_x as SO_2)	0.26	0.23	0.23	0.00	0.00

The net biomass CO_2 produced by the system is assumed to be zero. The positive values for biomass CO_2 reported in the results are assumed to be offset by biomass CO_2 uptake by the biomass during its growth. Plants use solar energy to fix carbon from carbon dioxide during photosynthesis. For this study, it is assumed that CO_2 uptake by the sugarcane plant will be released back to the environment through open-field burning of bagasse or through the burning of ethanol and lignin residue emanating from bagasse. Thus, the net CO_2 balance for growing and disposal of biomass is zero. Therefore, biomass-derived CO_2 is not used in the impact assessment phase to calculate greenhouse gas potential.

8 Data Quality and Sources

For an LCA, there are two different types of data: primary and secondary [SETAC 1993b]. Primary data are obtained directly from individual production plants or companies. Secondary data are published sources such as databases, industry or government publications, journals, or books. Another kind of secondary data also include “educated guesses” or data coming from experts based on their knowledge in the field, but not published.

In general, the goals for data collection, quality, and utilization are to use the most recent data available that are representative of an industry or practice. The goals specifically for this study were to obtain data on the processes leading to the disposal of biomass, the conversion of biomass into ethanol, and the use of E10 and current gasoline.

8.1 Data Sources

As it is difficult to obtain data specific for the Indian scenario, and given the limited scope and budget of this project, most of the data used is of U.S. or European origin (see Table 19).

However, this should not detract from the results because they can be viewed as a first approximation of what benefits can be achieved in India.

Table 19. Data sources and quality

Data Category	Description	Source Type and Date	Geographic and Temporal Representation	Reliability and Completeness
Biomass burning	Materials, emissions	Secondary/primary; EPA AP-42, CARB (1997)	United States 1990s	Reliable but incomplete because the emissions do not take into account the effect of burning conditions
Ethanol production	Materials, energy, emissions	Primary; NREL (1999)	United States 1990s	Reliable and complete (based on bench-scale data and process modeling)
Electricity production	Materials, energy, emissions	Secondary	India 1990s	Reliable and complete
Steam production	Materials, energy, emissions	Secondary; EPA AP-42 (1997)	United States 1980s, 1990s	Reliable and complete
Gasoline production and use	Materials, energy, emissions	Secondary; see references in Kadam et al. (1999)	Europe, World 1980s, 1990s	Reliable and complete
E10 use	Materials, emissions	Secondary; EPA AP-42 (1997), CRF (1999)	United States 1990s	Reliable and complete

8.2 Data Quality

Data in an LCA should have indicators for reliability and completeness. The *reliability indicator* pertains to how data were obtained and verified, independent of the data quality goals outlined in the study. The *completeness indicator* pertains to how representative the data samples are, i.e., do the data represent an adequate sample size, and do the data cover an adequate period such that normal fluctuations are evened out? The completeness indicator is also treated as independent of the data quality goals outlined in the study. Currently, actual data indicators have not been established in LCA guidelines. Instead, a table is generally provided to indicate the type of data in each life cycle sector and the reliability and completeness for each. Table 19 provides the general data categories in this study and provides a description of each, the sources and whether they are primary or secondary, a "checklist" of the reliability criteria, including the geographical and temporal extent of the data, and limitations.

9 RESULTS AND DISCUSSION

9.1 Presentation of Results

The results are presented here for the two different scenarios: burning versus diverting bagasse to ethanol. For each scenario, two methods of ethanol production are evaluated: dilute acid process and enzyme process. As mentioned earlier, the basis chosen for the comparison of the two different biomass disposal options is *1 dry t* of bagasse.

9.2 Explanation of Negative Flows

There are some negative values in the summary tables and in the figures, which arise from the electricity offset of the ethanol scenario. Besides actual flows, percentage differences are also included, which indicate the degree to which the values for the ethanol scenario (Scenario 2) were different from those for the burning scenario (Scenario 1), i.e.,

$$\%\,Difference = \frac{Scenario\,1\ value - Scenario\,2\ value}{Scenario\,1\ value} \times 100$$

A positive value indicates the percentage by which the values for the ethanol scenario were lower than those for the burning scenario, and vice versa.

9.3 Hydrocarbon Emission

As individual speciated emissions data are not available for all modules, all speciated non-methane hydrocarbon flows have been aggregated to give a value for the net hydrocarbon emissions. These include volatile organic compounds (VOCs), ethanol (air emissions), furfural, hydroxymethyl furfural (HMF), aldehydes, benzene, and hydrocarbons (except methane).

9.4 Time-Space Implications of Emissions

It should be noted that this report shows the life-cycle emissions of the two options without considering the spatial and temporal attributes, meaning that the results are aggregated over different locations and different time frames. Therefore, it does not take into account the fact that open burning results in a pulse of emissions at one time and location versus ethanol combustion in a vehicle that takes place over a period of time and at different locations. This report only shows the difference in the total emissions of the two options and does not account for concentrations of pollutants at a given time.

9.5 Life Cycle Energy Balance

The energy use of the competing scenarios is one measure of their overall environmental performance. LCIs provide an opportunity to quantify both the total energy demands and the overall energy efficiencies of processes and products. In this study, several different types of energy flows are tracked through each life cycle. For clarity, each of these energy flows is defined below.

Table 20. Explanation of negative flows

	Flow	Negative Value in the Totals for Each Option	Negative Value in the % Difference Column
Inflows	All raw material inflows	Indicates an offset that is greater than the use of materials for the option. Primarily due to electricity offset of energy-related materials.	Indicates that the ethanol option has higher raw material inflows than the burning option. **(Unfavorable to ethanol scenario)**
Outflows	All air emissions, water effluents, and solid waste	Indicates that electricity offset is greater than the emission of the pollutant for the option resulting in a net negative value.	Indicates that the ethanol option has higher emissions than the burning option. **(Unfavorable to ethanol scenario)**
Energy	Nonrenewable energy	Indicates that electricity offset is greater than the energy use of the option resulting in a net negative value.	Indicates that the ethanol option has higher nonrenewable energy use than the burning option. (**Unfavorable to ethanol scenario**)
	Renewable energy		Indicates that the ethanol option has higher renewable energy use than the burning option. (**Favorable to ethanol scenario**)
	Total primary energy		Indicates that the ethanol option has higher total energy use than the burning option. (**Unfavorable to ethanol scenario**)

- *Total Primary Energy*. All raw materials extracted from the environment can contain[2] energy. In estimating the total primary energy inputs to each life cycle, the cumulative energy content of all resources extracted from the environment is considered.

[2]The energy “contained” in a raw material is the amount of energy that would be released by the complete combustion of that raw material. This “heat of combustion” can be measured in two different ways: as a higher heating value or a lower heating value. Combustion results in the formation of CO_2 and water. Higher heating values consider the amount of energy released when the final combustion products are gaseous carbon dioxide and liquid water. Lower heating values take into account the loss of energy associated with the vaporization of the liquid water combustion product. The energy content used is based on the lower heating values for each material.

- *Feedstock Energy*. Energy contained in raw materials that end up directly in the final product is termed "feedstock energy." For ethanol production, feedstock energy includes the energy contained in the biomass. Feedstock energy is a subset of the primary energy inputs.
- *Process Energy*. The second major subset of primary energy is "process energy." This is limited to energy inputs in the life cycle exclusive of the energy contained in the feedstock (as defined in the previous bullet). It is the energy contained in raw materials extracted from the environment that does not contribute to the energy of the product itself, but is needed in the processing of feedstock energy into its final product form. Process energy is primarily from coal, natural gas, uranium, and hydroelectric power consumed directly or indirectly in the product life cycle.
- *Fossil or Nonrenewable Energy*. The primary energy that comes from fossil sources specifically (coal, oil, and natural gas) is tracked because it is important to distinguish between fossil and non-fossil energy. All three of the previously defined energy flows can be categorized as fossil or nonfossil energy.
- *Renewable Energy*. Renewable energy refers to energy obtained from biomass sources and also to electricity production from renewable sources such as biomass and hydroelectricity.

In the summary tables, the following energy values are reported: 1) process energy, 2) fossil or nonrenewable energy, 3) renewable energy, and 4) total primary energy. Criteria air pollutants are linked to the use of both nonrenewable and renewable energy, whereas natural resource depletion[3] and fossil CO_2 emissions are only linked to nonrenewable sources. Renewable energy use in Scenario 1 refers to renewable resources used to produce a portion of electricity used. Process energy indicates the net energy input to the process and can be useful in comparing process options.

9.6 LCI for Burning versus Diverting Bagasse to Ethanol: Enzyme Process

For the enzyme process, Scenario 2 leads to a decrease from Scenario 1 for almost all of the key environmental flows (Table 21). The various environmental flows and their implications of these are discussed below. Natural gas consumption and CODs for key modules are given in Table 22; this allows explanation of higher values for these environmental flows in Scenario 2.

[3]Soil erosion is not included in the calculation of natural resource depletion because data were not available. The effects of biomass harvesting on soil erosion is more difficult to quantify than the removal of other natural resources, e.g., coal and oil.

Table 21. Life cycle inventory for burning versus diverting bagasse to ethanol: Summary for enzyme process

	Flow	Units	Scenario 1: Burning + Gasoline use	Scenario 2: Ethanol Production + E10 use	Change from Scenario 1 to Scenario 2
			Per t of bagasse		%
Inflows	Coal (in ground)	kg	5.5	-100.7	1938
	Lignite (in ground)	kg	0.02	-0.01	149
	Natural gas (in ground)	kg	17.7	23.1	-30
	Oil (in ground)	kg	172.9	4.4	98
	Water used (total)	liter	761	-73	110
Outflows					
Air	Carbon Dioxide (CO_2, biomass)	kg	1,706	1,625	5
	Carbon Dioxide (CO_2, fossil)	kg	521	-77	115
	Carbon Monoxide (CO)	g	69	23	66
	Hydrocarbons (except methane)	g	8.7	10.2	-17
	Lead (Pb)	g	30.9	-0.14	101
	Methane (CH_4)	g	8,465	-149	102
	Nitrogen Oxides (NO_x as NO_2)	kg	8.5	4.5	47
	Nitrous Oxide (N_2O)	g	20	21	-3
	Particulates (unspecified)	g	4,195	148	97
	Sulfur Oxides (SO_x as SO_2)	g	2,622	1,774	32
Water	COD (Chemical Oxygen Demand)	g	25.8	123.8	-381
	Lead (Pb^{++}, Pb^{4+})	g	0.0085	-0.0034	140
	Nitrates (NO^{3-})	g	2.3	-0.05	102
Solid	Waste: total	kg	41.0	-13.7	134
	Waste: hazardous	kg	0.20	-0.01	107
	Waste: radioactive total	kg	0.017	-0.0002	101
Energy	Process energy	MJ	21,114	12,625	40
	Nonrenewable energy	MJ	8,508	226	97
	Renewable energy	MJ	8.4	18,841	NM[a]
	Total primary energy	MJ	27,517	19,068	31

[a]Not meaningful to report.

Table 22. Natural gas consumption and CODs for key modules

	Basis	Natural gas, g	COD, g
Ammonia	1 kg	0.91	3.72
Sulfuric acid	1 kg	0.04	1.4×10^{-5}
Lime	1 kg	0.10	2.6×10^{-5}
Diesel production	1 kg	0.14	3.47
Gasoline production	1 kg	0.11	0.17
Steam	1 kg	0.063	0.002
Electricity	1 MJ	0.053	2.1×10^{-4}

9.6.1 Resource Depletion

Depletion of nonrenewable resources is an important criterion in judging alternative scenarios. Coal and lignite usage is negative for Scenario 2 due to offset credits from excess electricity (Figure 8). Natural gas usage is higher (Figure 9) and crude oil usage is significantly lower (Figure 10) for Scenario 2 compared to Scenario 1. The reason that natural gas usage is higher for Scenario 2 is because of the ammonia use during ethanol production, which is absent in Scenario 1 (see Table 22). Water usage is also is negative for Scenario 2 owing to offset credits (Figure 11). Depletion of non-renewable resources is also captured in impact assessment (section 9.8).

9.6.2 Air Pollutants

CO emissions for Scenario 2 are a third of those for Scenario 1, which is a significant benefit for Scenario 2 (Figure 12). Nonmethane hydrocarbon emissions are slightly higher for Scenario 2 than those for Scenario 1 (Figure 13). About half of the Scenario 2 hydrocarbon emissions are from ethanol, furfural, and hydroxy-methyl-furfural (HMF) emitted during ethanol production, which is absent in Scenario 1. SO_x emissions for Scenario 2 are lower by about 30%, while NO_x emissions for Scenario 2 are lower by about 50% (Figure 14 and Figure 15). Also, particulate emissions are lower for Scenario 2 by a factor of about 30, again a large reduction for an important air pollutant (Figure 16). It should be noted that most of the particulate emissions and a bulk of the CO emissions are from biomass burning in Scenario 1. Lead emissions are lower for Scenario 2 due to the partial displacement of gasoline by ethanol (Figure 17).

9.6.3 Waste Generation

Nitrates and lead (water-borne) emissions are lower but COD values are significantly higher for Scenario 2 compared to those for Scenario 1. The higher COD values for Scenario 2 stem from the ethanol production step. However, water emissions do not occur during the actual process, but rather during upstream production of raw materials used in the process, e.g., ammonia, sulfuric acid, lime, etc. As shown in Table 22, COD values are especially high for ammonia, which is used only in Scenario 2. Moreover, electricity offsets for COD are very low.

Total solid waste, hazardous waste, and radioactive waste are lower for Scenario 2 compared to that for Scenario 1. Lime is a big contributor to the total solid waste, while ammonia and sulfuric acid also are responsible for some of the waste generation. These raw materials are used only in Scenario 2. In spite of this, solid wastes are lower for Scenario 2 compared to those for Scenario 1, mainly because of electricity offsets.

9.6.4 Energy Consumption and GHGs

Due to electricity offset credits, negative CO_2 and CH_4 emissions are encountered, thereby more than mitigating all the CO_2 and methane emissions from Scenario 1 (Figure 18 and Figure 19). The slightly higher nitrous oxide emissions for Scenario 2, if considered significant, can be explained by the use of diesel in transporting bagasse. This burden is absent in Scenario 1, and electricity offsets do not affect nitrous oxide emissions. Process energy required is less for Scenario 2 by 40% (Figure 20), and its nonrenewable energy consumption is 97% lower compared to that for Scenario 1 (Figure 21). As expected, the renewable energy consumption is very high for Scenario 2 and very low for Scenario 1.

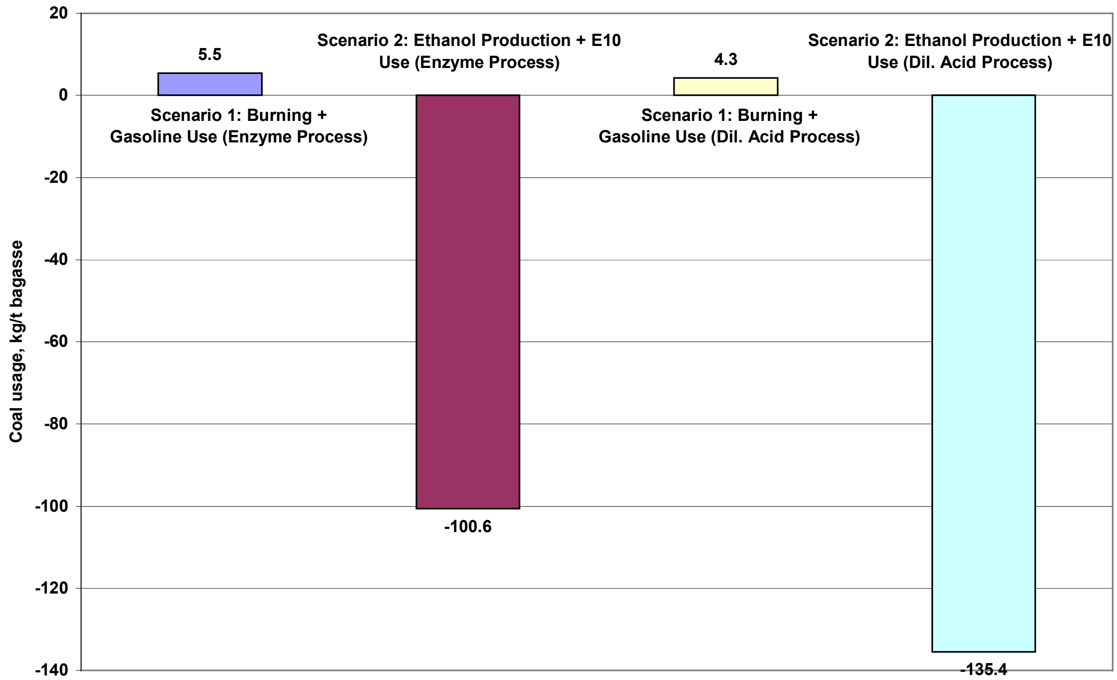

Figure 8. Comparison of burning versus diverting bagasse to ethanol: Coal usage.

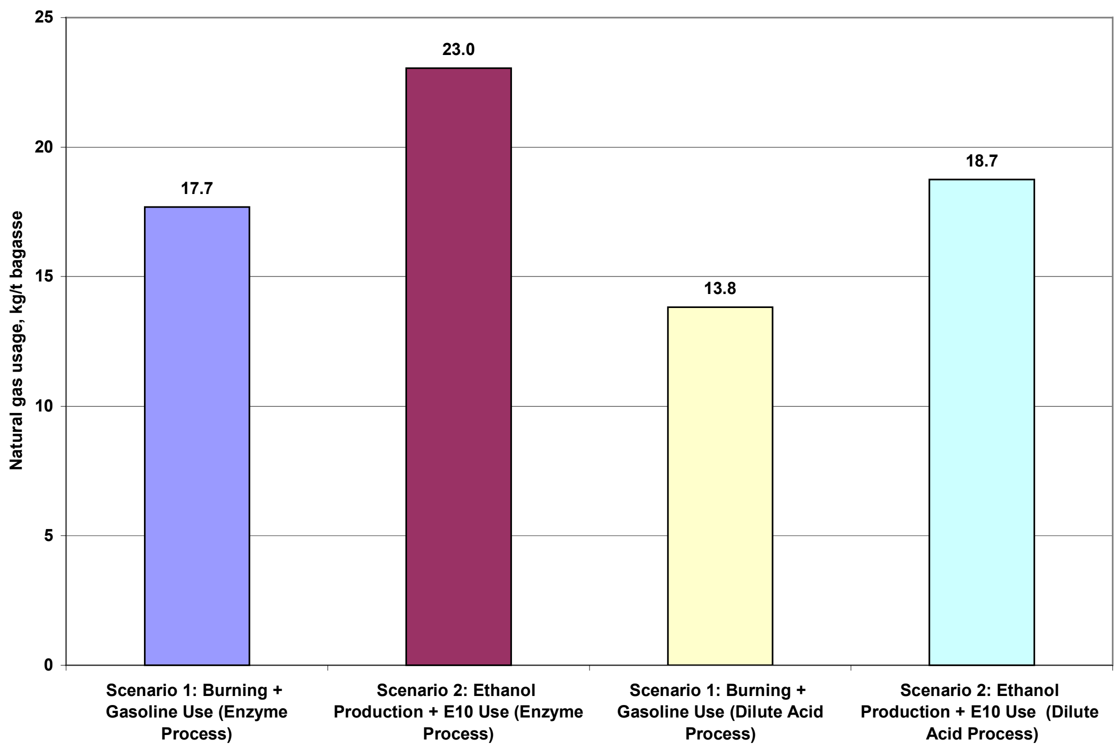

Figure 9. Comparison of burning versus diverting bagasse to ethanol: Natural gas usage.

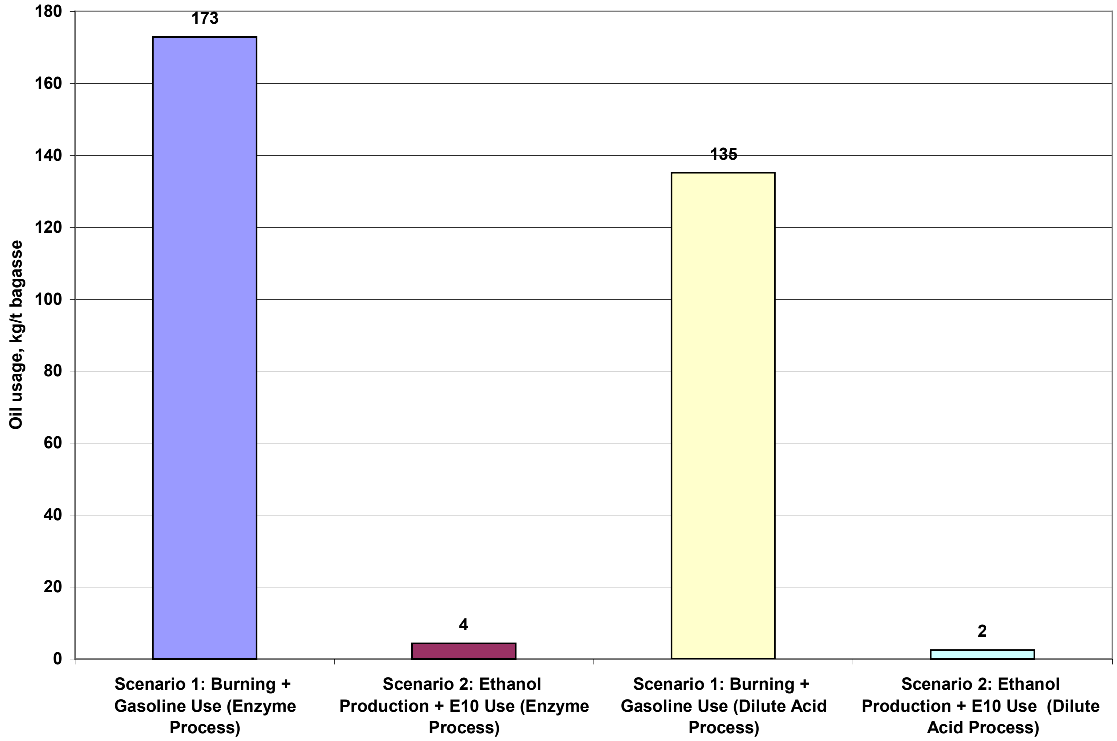

Figure 10. Comparison of burning versus diverting bagasse to ethanol: Crude oil usage.

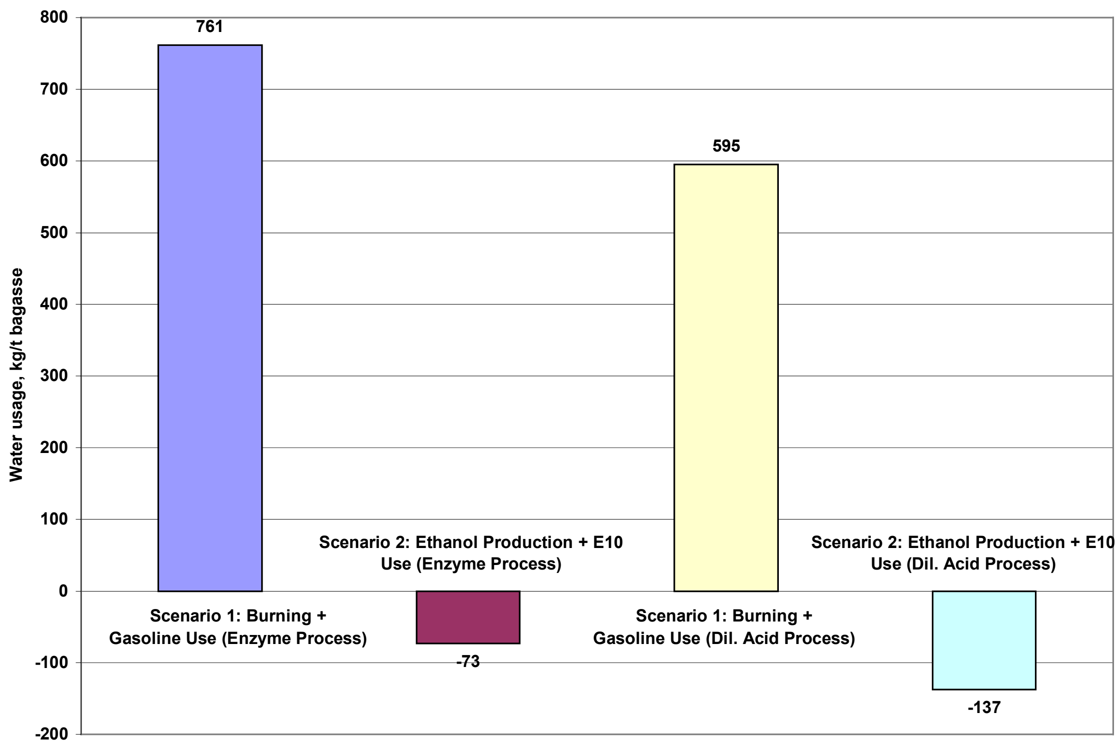

Figure 11. Comparison of burning versus diverting bagasse to ethanol: Water usage.

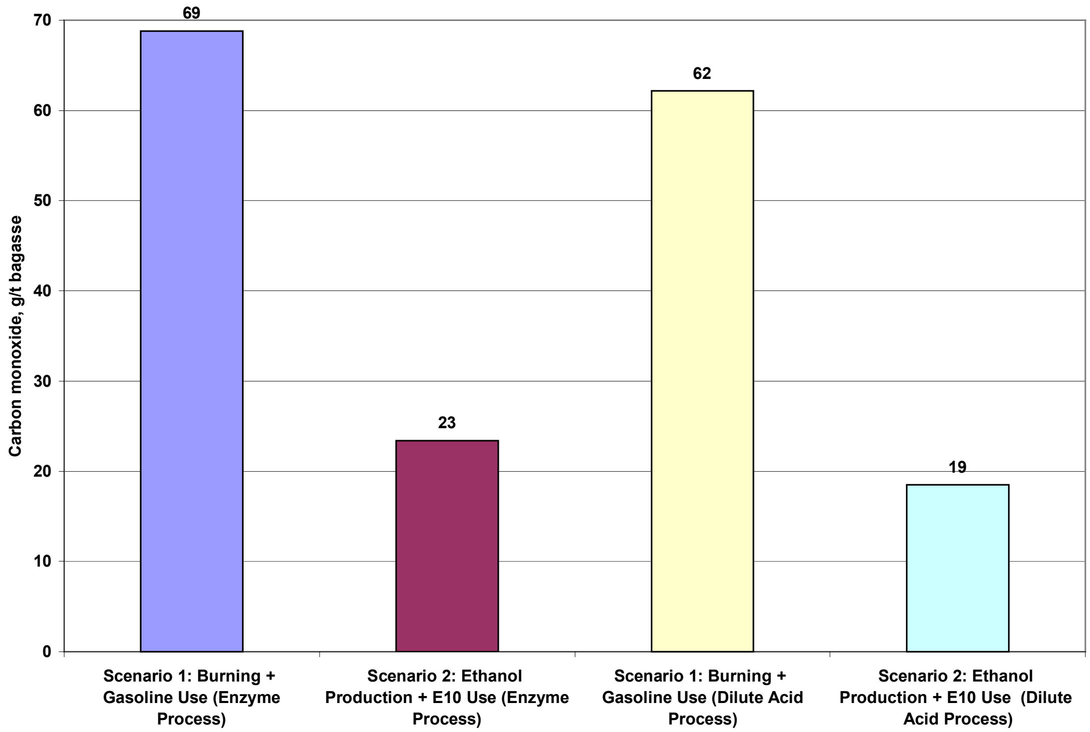

Figure 12. Comparison of burning versus diverting bagasse to ethanol: Carbon monoxide emissions.

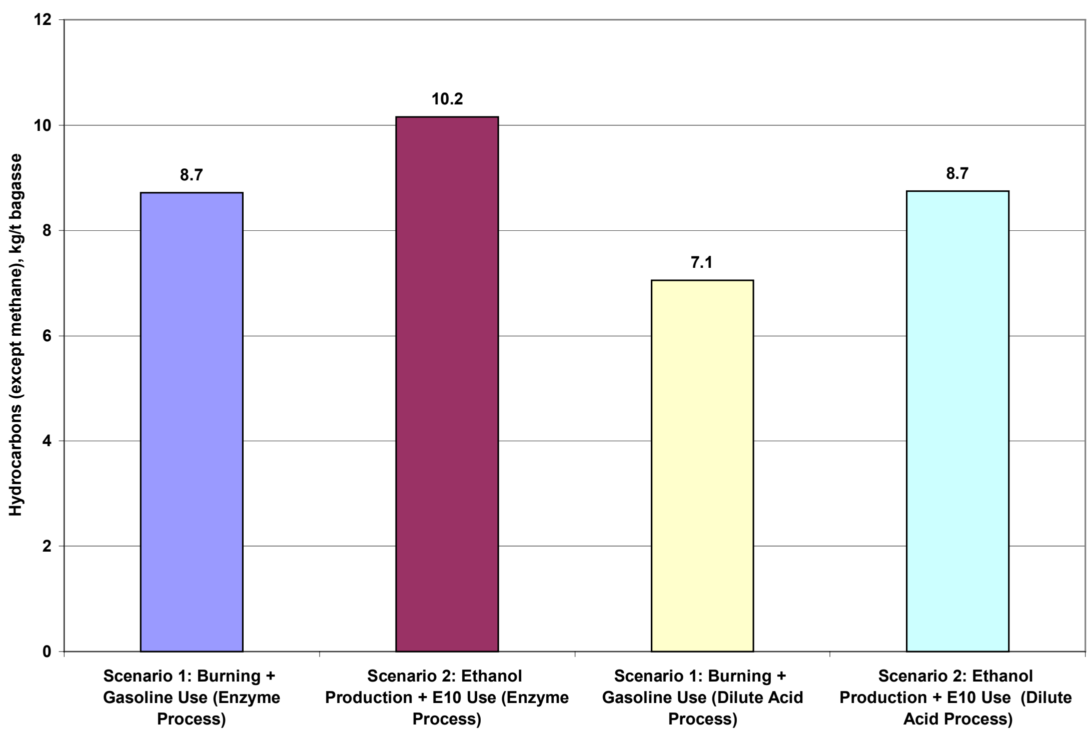

Figure 13. Comparison of burning versus diverting bagasse to ethanol: Hydrocarbon (except methane) emissions.

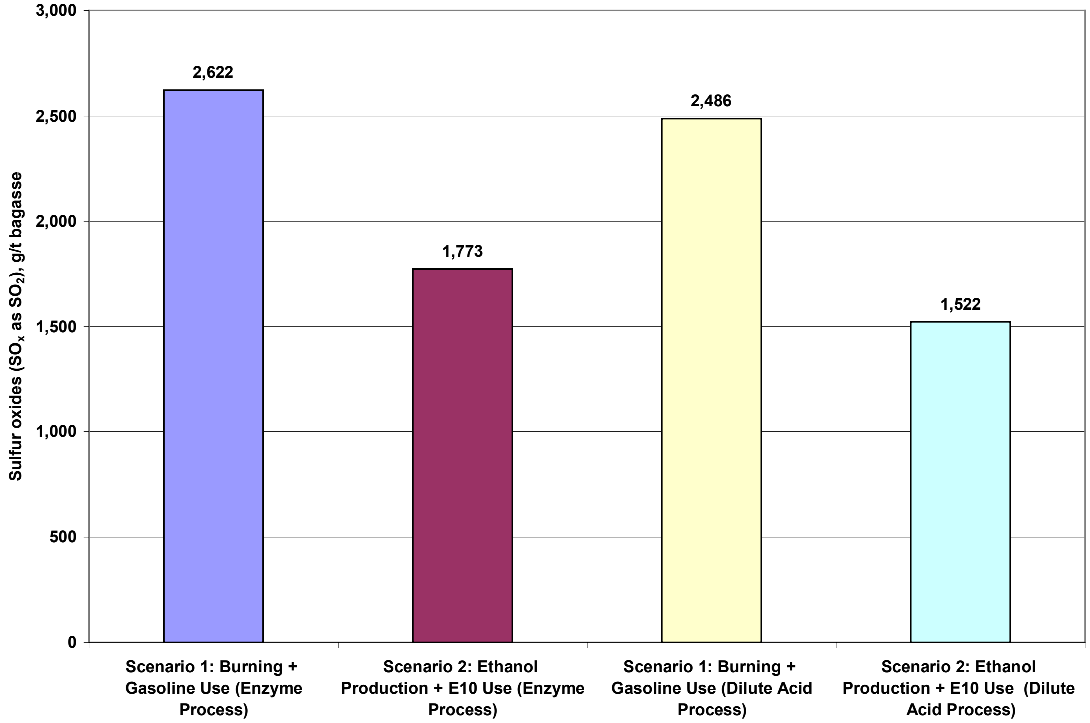

Figure 14. Comparison of burning versus diverting bagasse to ethanol: Sulfur oxides (SO_x as SO_2) emissions.

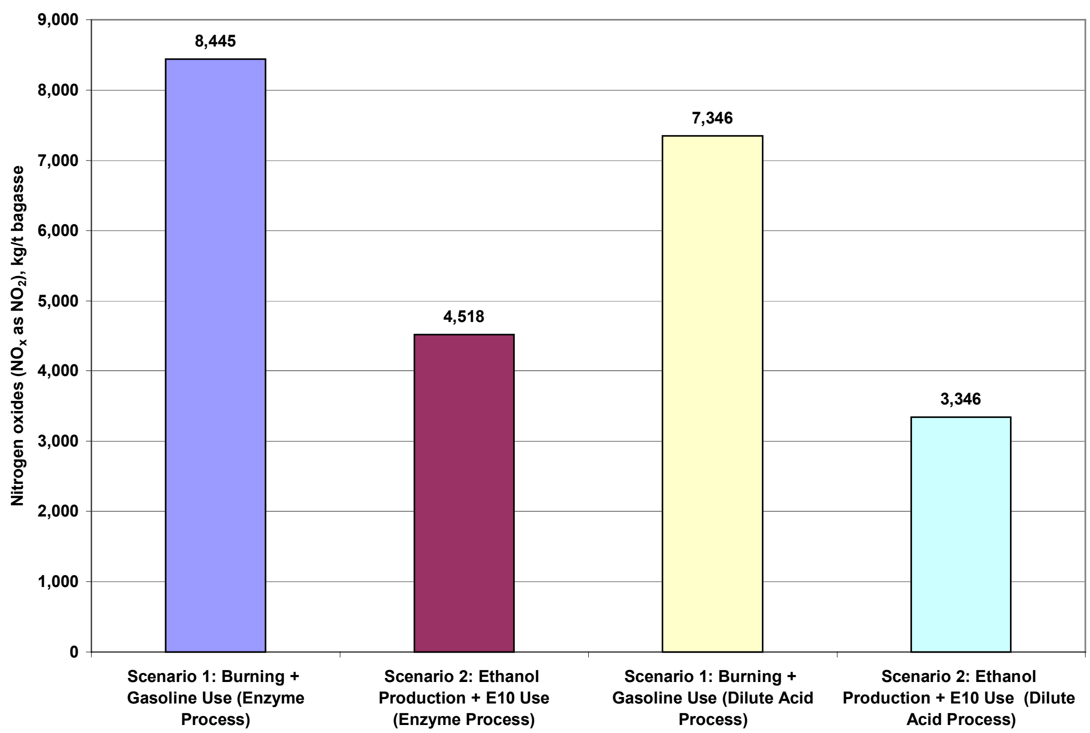

Figure 15. Comparison of burning versus diverting bagasse to ethanol: Nitrogen oxides (NO_x as NO_2) emissions.

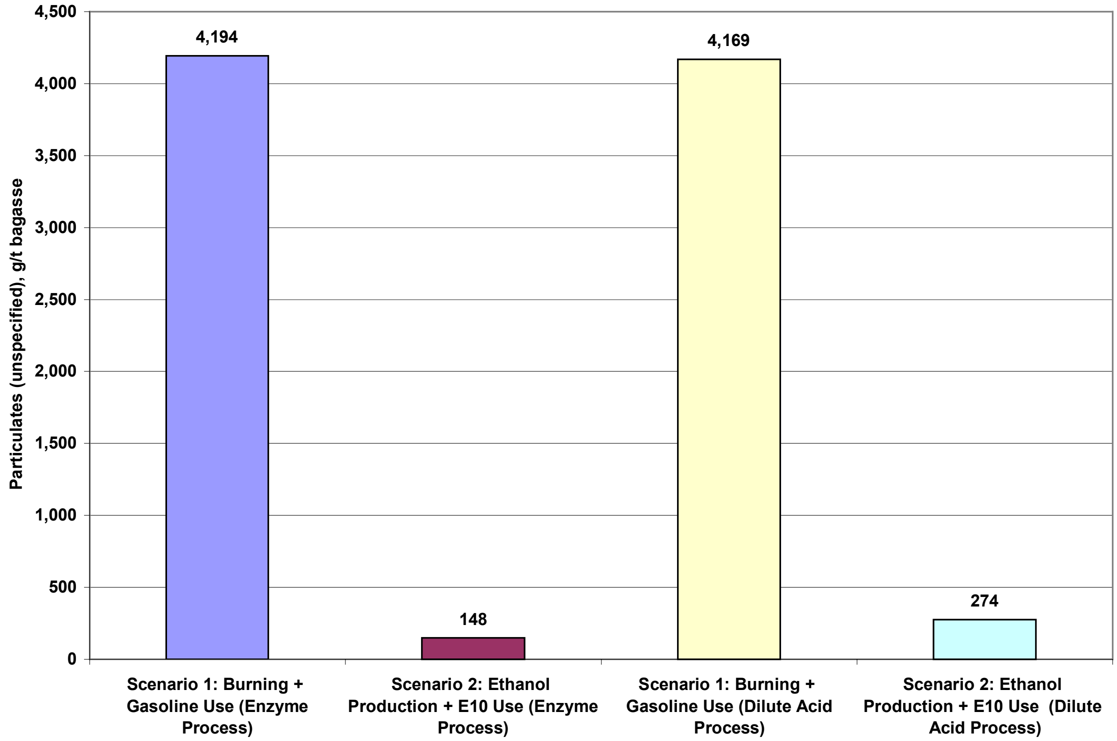

Figure 16. Comparison of burning versus diverting bagasse to ethanol: Particulate matter (unspecified) emissions.

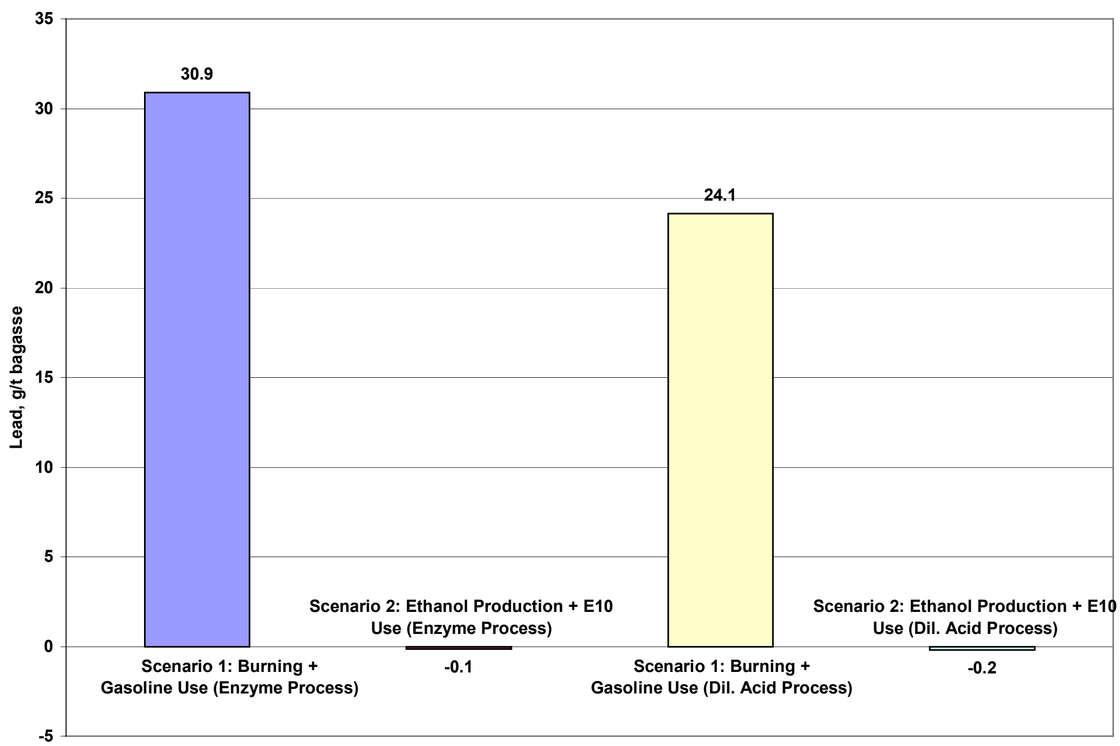

Figure 17. Comparison of burning versus diverting bagasse to ethanol: Lead emissions.

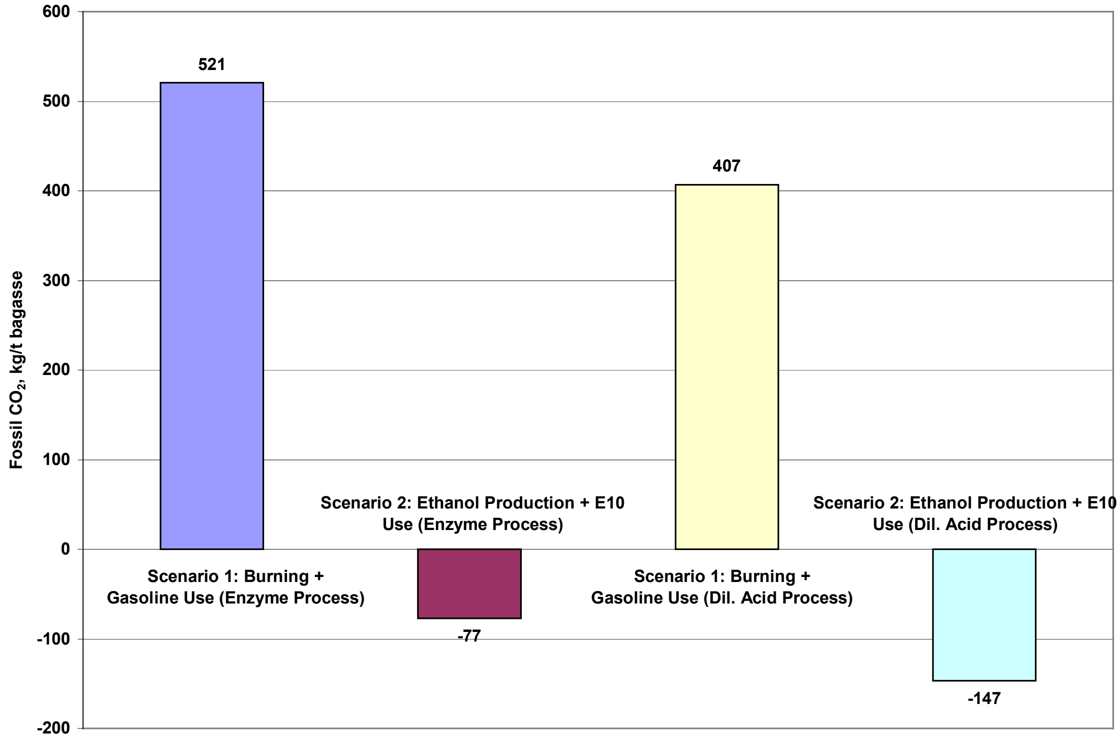

Figure 18. Comparison of burning versus diverting bagasse to ethanol: Fossil CO_2 emissions.

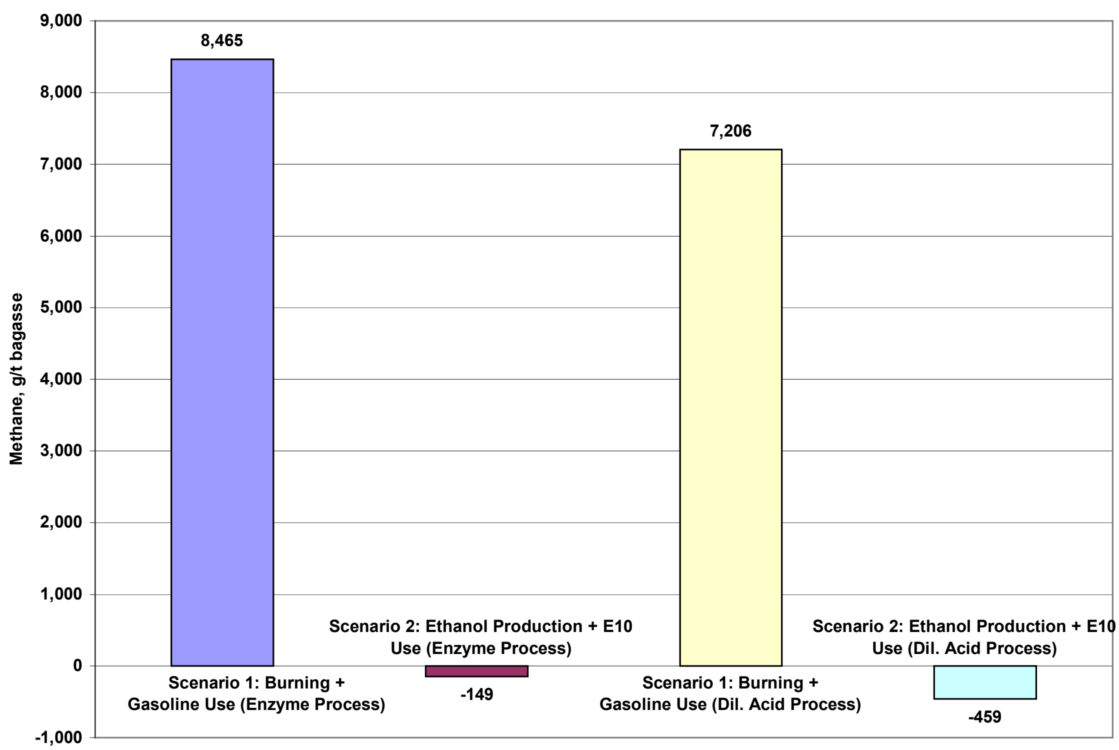

Figure 19. Comparison of burning versus diverting bagasse to ethanol: Methane emissions.

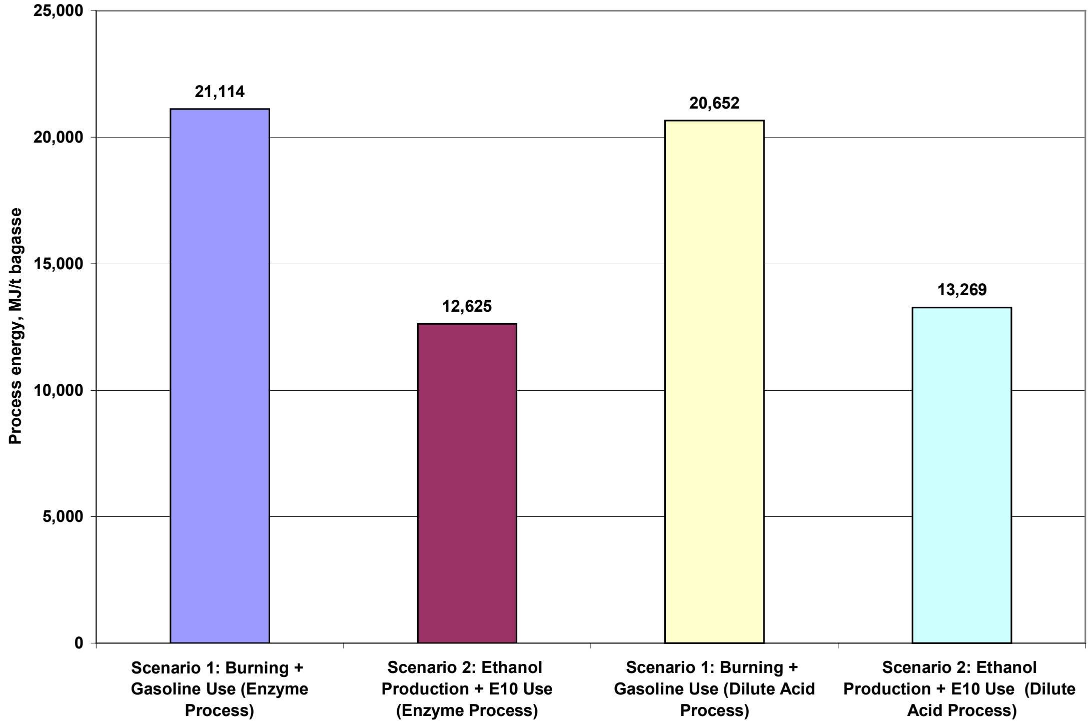

Figure 20. Comparison of burning versus diverting bagasse to ethanol: Process energy usage.

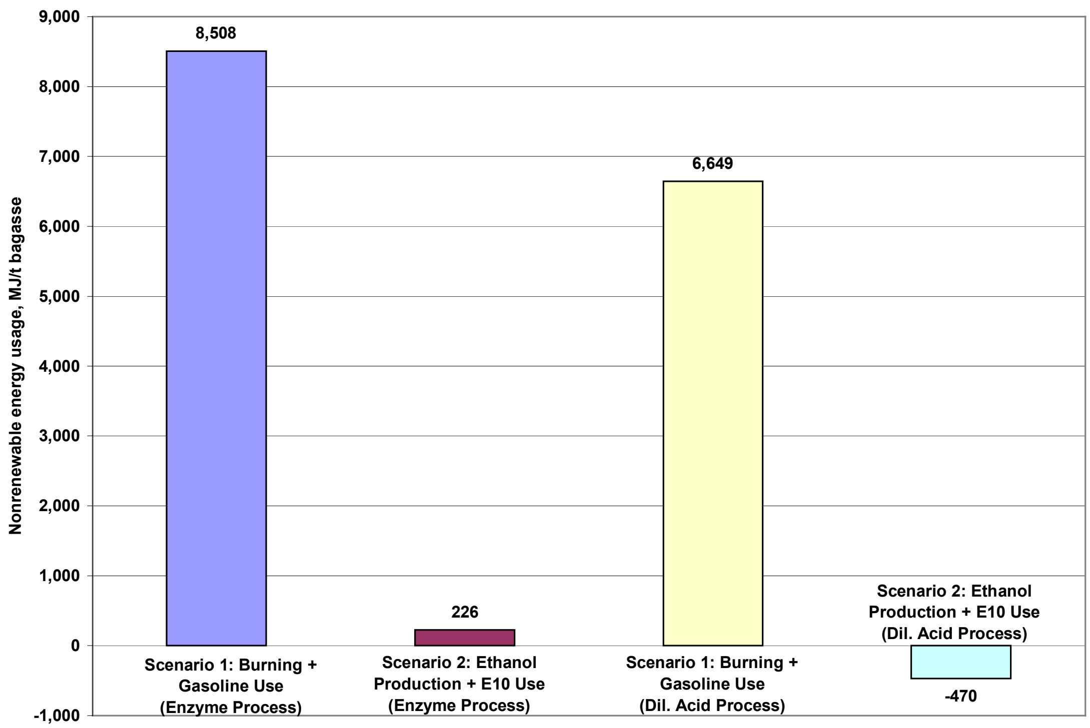

Figure 21. Comparison of burning versus diverting bagasse to ethanol: Nonrenewable energy usage.

9.7 LCI for Burning versus Diverting Bagasse to Ethanol: Dilute Acid Process

Similar results for key environmental flows are obtained using the dilute acid process (Table 23), the specific changes from Scenario 1 to Scenario 2 being affected by the inherent differences in the two processes.

Table 23. Life cycle inventory for burning versus diverting bagasse to ethanol: Summary for dilute acid process

		Units	Scenario 1: Burning + Gasoline use	Scenario 2: Ethanol Production + E10 use	Change from Scenario 1 to Scenario 2
			Per t of bagasse		%
Inflows	Coal (in ground)	kg	4.3	-135.4	3265
	Lignite (in ground)	kg	0.017	-0.014	184
	Natural gas (in ground)	kg	13.8	18.8	-36
	Oil (in ground)	kg	135	2.5	98
	Water used (total)	liter	595	-137	123
Outflows					
Air	Carbon Dioxide (CO_2, biomass)	kg	1,706	1,663	3
	Carbon Dioxide (CO_2, fossil)	kg	407	-147	136
	Carbon Monoxide (CO)	g	62	19	70
	Hydrocarbons (except methane)	g	7.1	8.8	-24
	Lead (Pb)	g	24	-0.2	101
	Methane (CH_4)	g	7,206	-459	106
	Nitrogen Oxides (NO_x as NO_2)	kg	7.4	3.4	55
	Nitrous Oxide (N_2O)	g	16.0	15.6	2
	Particulates (unspecified)	g	4,169	274	93
	Sulfur Oxides (SO_x as SO_2)	kg	2.5	1.5	39
Water	COD (Chemical Oxygen Demand)	g	20	109	-442
	Lead (Pb^{++}, Pb^{4+})	g	0.0067	-0.0046	168
	Nitrates (NO^{3-})	g	1.8	-0.1	104
Solid	Waste: total	kg	40	5	88
	Waste: hazardous	kg	0.16	-0.02	112
	Waste: radioactive total	kg	0.01	-0.0003	102
Energy	Process energy	MJ	20,652	13,269	36
	Nonrenewable energy	MJ	6,649	-470	107
	Renewable energy	MJ	6.6	18,787	NM[a]
	Total primary energy	MJ	25,656	18,317	29

[a]Not meaningful to report.

9.7.1 *Resource Depletion*

Coal, lignite, and water usage is again negative due to offset credits. Natural gas usage is again higher; however, crude oil usage is significantly lower. The reason for higher natural gas usage is the same as in the case of the enzyme process.

9.7.2 *Air Pollutants*

CO_2 emissions for Scenario 2 are again a third of those for Scenario 1. Also, particulate emissions are lower for Scenario 2 by a factor of about 15. As in the case of the enzyme process, most of the particulate and CO_2 emissions are from biomass burning in Scenario 1. SO_x emissions for Scenario 2 are lower by a factor of about 2, while NO_x emissions for Scenario 2 are lower by 55%. In general, reductions are higher for the dilute acid process as compared to the enzyme process, because of the higher offsets enjoyed by the former. More of the bagasse is sent as fuel residue to the boiler. This leads to lower SO_x, NO_x, and fossil CO_2 emissions because of the correspondingly high electricity offset credits. Again, about 50% of the Scenario 2 hydrocarbon emissions are from ethanol, furfural, and HMF emitted during ethanol production, which yields higher hydrocarbon emissions for Scenario 2 compared to Scenario 1.

9.7.3 *Waste Generation*

As in the enzyme case, COD values are significantly higher for Scenario 2 compared to those for Scenario 1. The explanation given above for higher COD values for Scenario 2 applies here as well.

Total solid waste, hazardous waste, and radioactive waste are again lower for Scenario 2 compared to that for Scenario 1, but the decrease for Scenario 2 is lower than that for the enzyme case. This is because the acid process uses more lime than the enzyme process, and lime is the single largest contributor to total solid waste generation.

9.7.4 *Energy Consumption and GHGs*

Process energy required is less for Scenario 2 by 36% compared to that for Scenario 1. As in the enzyme case, the nonrenewable energy offset yields a negative value for Scenario 2 giving negative CO_2 and methane emissions. The nitrous oxide emissions are about the same for both scenarios.

9.8 LCIA for Burning versus Diverting Bagasse to Ethanol

In addition to the environmental flows, impact indicator values were also calculated for the above scenarios. These indicators are used to give a broader insight into the environmental impacts of the competing scenarios, by examining the potential impacts beyond the initial release. The indices calculated are greenhouse potential, natural resources depletion, acidification potential, eutrophication potential, human toxicity potential, air odor potential, and ozone-forming potential (see Appendix B for definitions). It should be emphasized that only fossil CO_2 was taken into account in calculating greenhouse potential. Table 24 and Table 25 give the overall values for these impact indicators. It is evident from these tables that for all the indicators, Scenario 1 is worse than Scenario 2, using either of the ethanol production schemes, with the exception of the EPA-maximum incremental reactivity potential, the reason for which is explained later.

Table 24. Life cycle impact assessment for burning versus diverting bagasse to ethanol: Summary for enzyme process

Impact	Units	Scenario 1: Burning + Gasoline Use	Scenario 2: Ethanol Production + E10 Use	Change from Scenario 1 to Scenario 2
		Per t of bagasse		%
IPCC-Greenhouse effect (direct, 100 years)[a]	kg equivalent CO_2	731	-73	110
Depletion of nonrenewable resources (CML)[b]	fraction of reserve	$8.7x10^{-13}$	$1.5x10^{-13}$	82
Air acidification (CML)[b]	g equivalent H^+	266	155	42
Eutrophication (CML)[b]	g equivalent PO_4	1,120	596	47
Human toxicity (CML)[b]	kg toxic compounds	16.8	5.7	66
Air odor (CML)[b]	m^3 air	609	-611	200
EPA-Maximum incremental reactivity potential	kg ozone equivalent	4.7	6.4	-36

[a]IPCC = Intergovernment Panel on Climate Change, United Nations.
[b]CML = Centre of Environmental Science, Leiden University, The Netherlands.

9.8.1 Greenhouse Potential

The greenhouse potential values for Scenario 1 are predominantly larger than the values for Scenario 2 (see also Figure 22). The reason behind this is the higher fossil energy use in Scenario 1, which leads to higher fossil CO_2 emissions. The difference between the two methods of producing ethanol is due to the higher electricity offsets for the acid process, i.e., higher credit for CO_2 emissions.

9.8.2 Natural Resource Depletion Potential

The natural resource depletion values are driven to a large degree by how much of a designated natural resource the system consumes, e.g., coal, oil, phosphate, natural gas, uranium, bauxite, iron, etc. The natural resource depletion values for Scenario 1 are driven by gasoline production. Once again, the amount of lignin residue produced during ethanol production leads to electricity offsets, which results in a reduction in natural gas, oil, and coal consumption. Hence, natural resource depletion index for Scenario 1 is larger than that for Scenario 2 (see also Figure 23).

Table 25. Life cycle impact assessment for burning versus diverting bagasse to ethanol: Summary for dilute acid process

Impact	Units	Scenario 1: Burning + Gasoline use	Scenario 2: Ethanol Production + E10 use	Change from Scenario 1 to Scenario 2
		Per t of bagasse		%
IPCC-Greenhouse effect (direct, 100 years)[a]	kg equivalent CO_2	586	-152	126
Depletion of nonrenewable resources (CML)[b]	fraction of reserve	6.8×10^{-13}	9.5×10^{-13}	86
Air acidification (CML)[b]	g equivalent H^+	238	120	49
Eutrophication (CML)[b]	g equivalent PO_4	972	441	55
Human toxicity (CML)[b]	kg toxic compounds	14.4	4.3	70
Air odor (CML)[b]	m^3 air	476	-2,817	692
EPA-Maximum incremental reactivity potential	kg ozone equivalent	4.2	5.7	-37

[a]IPCC = Intergovernment Panel on Climate Change, United Nations.
[b]CML = Centre of Environmental Science, Leiden University, The Netherlands.

9.8.3 Air Acidification Potential

Scenario 1 generates a larger acidification impact than the comparative ethanol production scenario (Figure 24). For Scenario 1, the use of electricity in gasoline production process generates most of the emissions that contribute to the acidification values. The burning of the bagasse itself also contributes to this impact value because bagasse has a relatively large sulfur content. However, both the scenarios experience the SO_x release when either bagasse is burned (Scenario 1) or the lignin residue is burned during cogeneration (Scenario 2). Similar to the greenhouse potential, the air acidification indicator values are affected by the electricity offset from lignin-based cogeneration. This is because electrical plants generate large amounts of SO_x and NO_x.

9.8.4 Eutrophication Potential

Eutrophication impact values are also higher for Scenario 1 than for Scenario 2 (Figure 25). The production of the fuel used to produce gasoline as well as that used during the transportation of the biomass were the main contributors to this value. The eutrophication values for Scenario 2 are also driven by the water-borne emissions from ethanol production. However, it is not the actual process that is the driver, but rather the upstream emissions from the production of raw materials used in the process (e.g., ammonia, sulfuric acid, lime, etc.). It should be noted that, unlike in the case of air-related impacts, the eutrophication potential is not greatly affected by the higher electricity offset credits. Despite this, Scenario 2 has lower eutrophication potential.

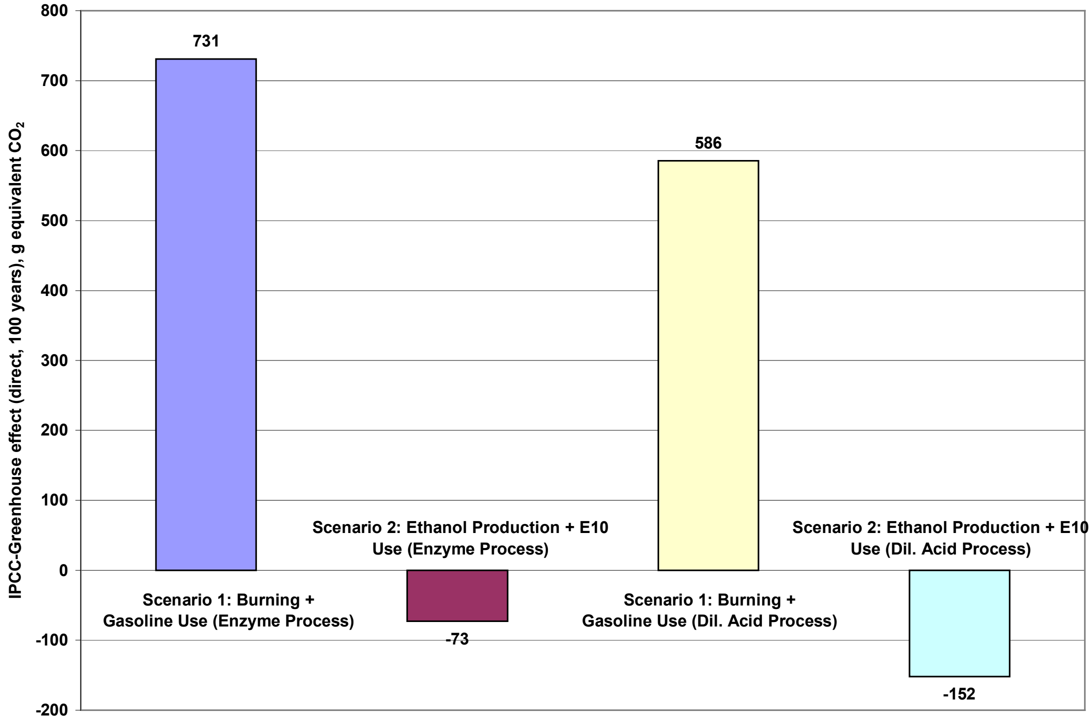

Figure 22. Comparison of burning versus diverting bagasse to ethanol: Greenhouse effect potential.

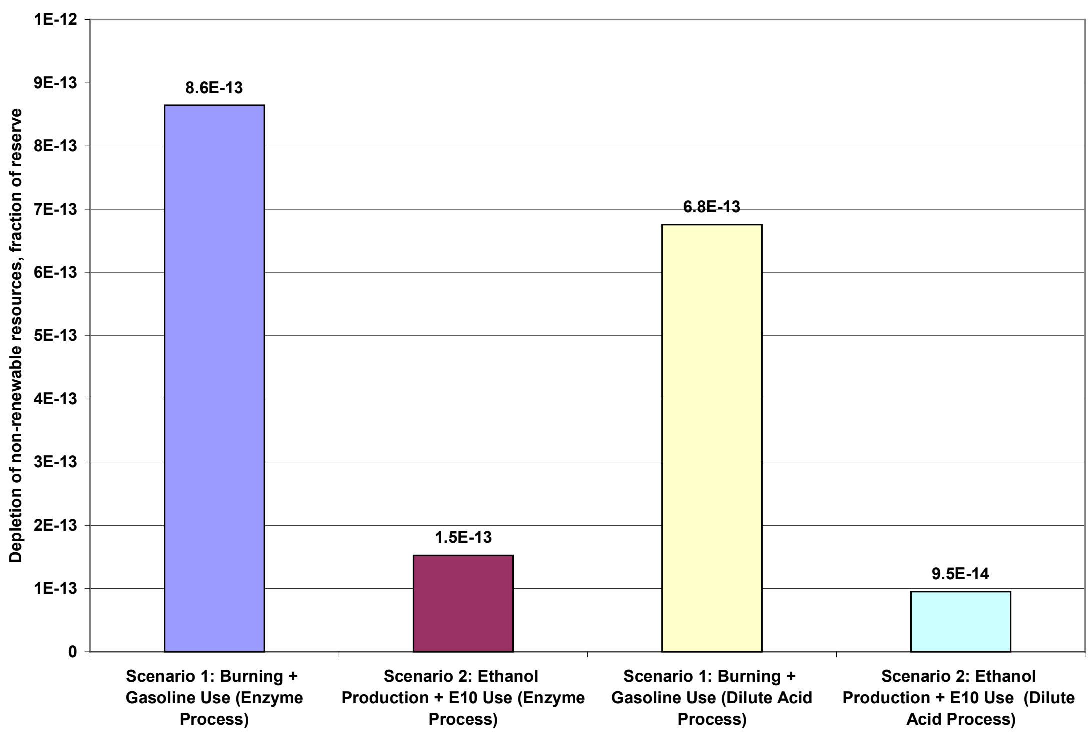

Figure 23. Comparison of burning versus diverting bagasse to ethanol: Depletion of non-renewable resources.

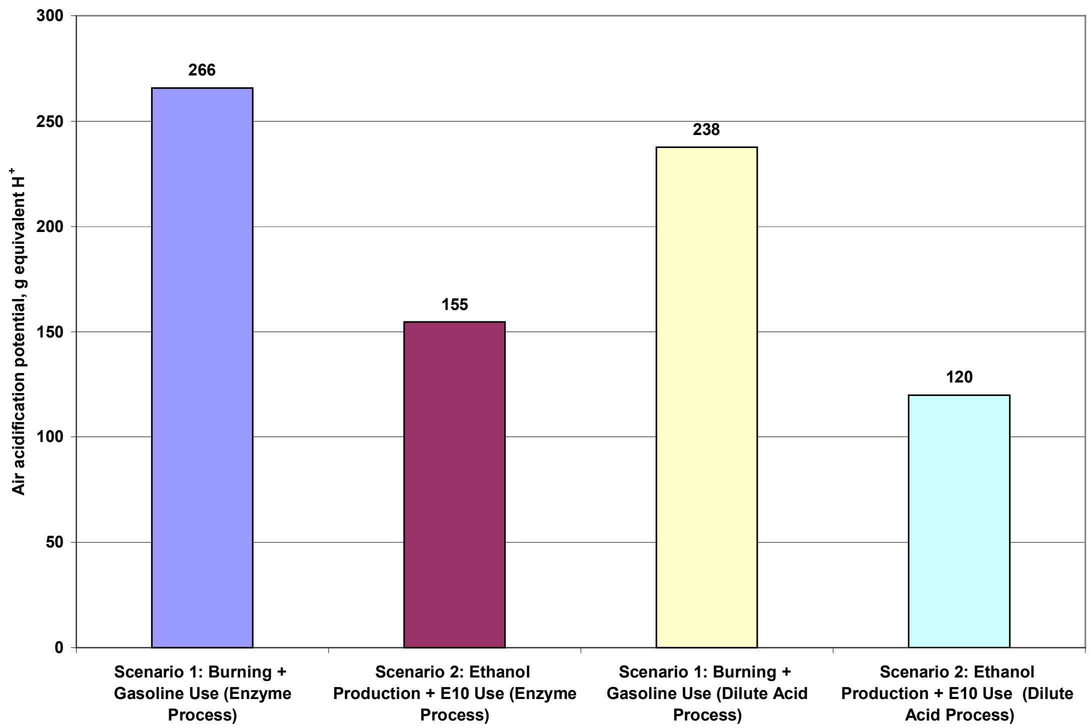

Figure 24. Comparison of burning versus diverting bagasse to ethanol: Air acidification potential.

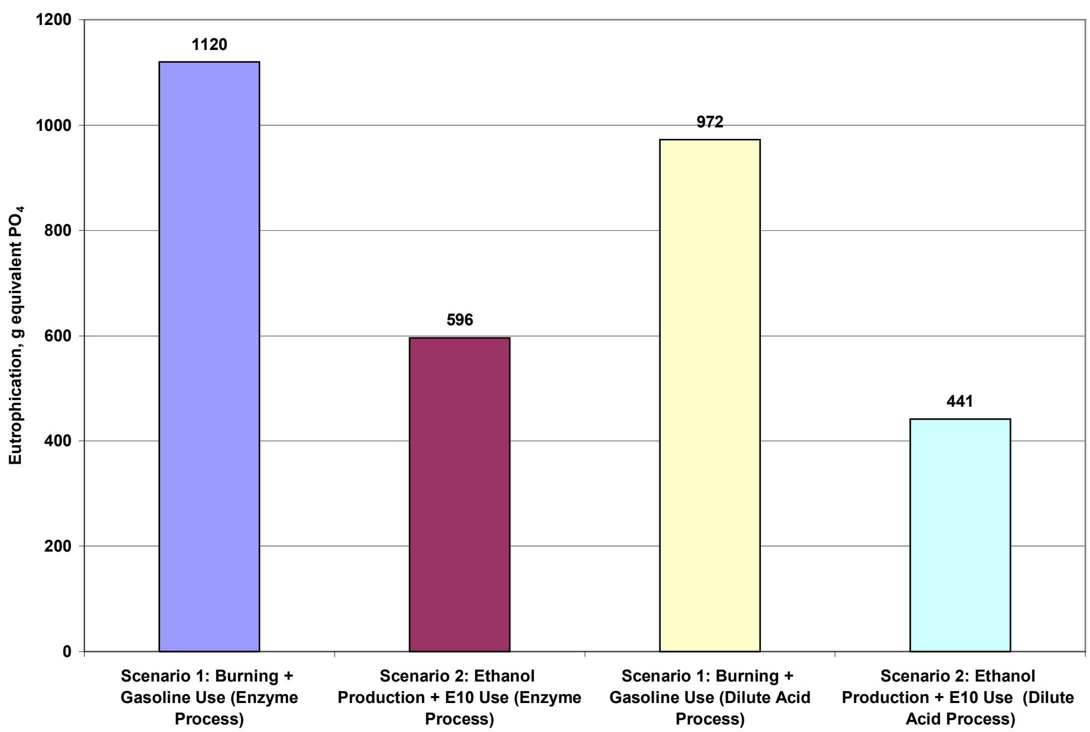

Figure 25. Comparison of burning versus diverting bagasse to ethanol: Eutrophication potential.

9.8.5 Human Toxicity Potential

The human toxicity potential is higher for Scenario 1 than for Scenario 2 (Figure 26). Gasoline production and burning activities in Scenario 1 contribute to its higher index value. This is not unexpected since this impact takes into account all the toxic compounds, both in air and water, and most of these emissions are higher for Scenario 1 than for Scenario 2.

9.8.6 Air Odor Potential

Although less obnoxious than the toxic emissions, this impact is also important to consider. The air odor index is higher for Scenario 1 than for Scenario 2 (Figure 27). Again, the burdens from gasoline production and burning in Scenario 1 play a role in its higher index value. Scenario 2 actually has negative index values, meaning that it offsets the odor impact of Scenario 1, and still has credits left in this realm.

9.8.7 Maximum Incremental Reactivity Potential

EPA-maximum incremental reactivity (MIR), or ozone-forming potential, as calculated by TEAM™, is somewhat higher for Scenario 2 than for Scenario 1. This is because nonmethane hydrocarbon emissions during burning are not speciated and could not be included in these calculations. The EPA-Maximum incremental reactivity potential is calculated by using individual emissions shown in Table 26 (this list includes only those compounds occurring in the processes and/or modules used in the current LCA model). Hence, the ozone impact from burning is not included in the impact for Scenario 1. Thus, it can be surmised that the actual MIR potential, although it cannot be accurately assessed, would be lower for Scenario 2 than for Scenario 1.

Table 26. Ozone-forming potential of selected compounds

Compound	Maximum incremental reactivity, g ozone	Compound	Maximum incremental reactivity, g ozone
Acetaldehyde (CH_3CHO)	6.322	Ethylene (C_2H_4)	8.287
Acetone (CH_3COCH_3)	0.4892	Formaldehyde (CH_2O)	7.009
Acetylene (C_2H_2)	0.567	Heptane (C_7H_{16})	1.045
Benzaldehyde (C_6H_5CHO)	-0.259	Hexane (C_6H_{14})	1.223
Benzene (C_6H_6)	0.601	Methane (CH_4)	0.016
Butane (n-C_4H_{10})	1.255	Methanol (CH_3OH)	0.627
Butene (1-$CH_3CH_2CHCH_2$)	10.68	Phenol (C_6H_5OH)	1.37
Carbon Monoxide (CO)	0.061	Propane (C_3H_8)	0.577
Ethane (C_2H_6)	0.299	Propionaldehyde (CH_3CH_2CHO)	7.592
Ethanol (C_2H_5OH)	1.622	Propylene (CH_2CHCH_3)	11.14
Ethyl Benzene ($C_6H_5C_2H_5$)	3.11	Toluene ($C_6H_5CH_3$)	3.154

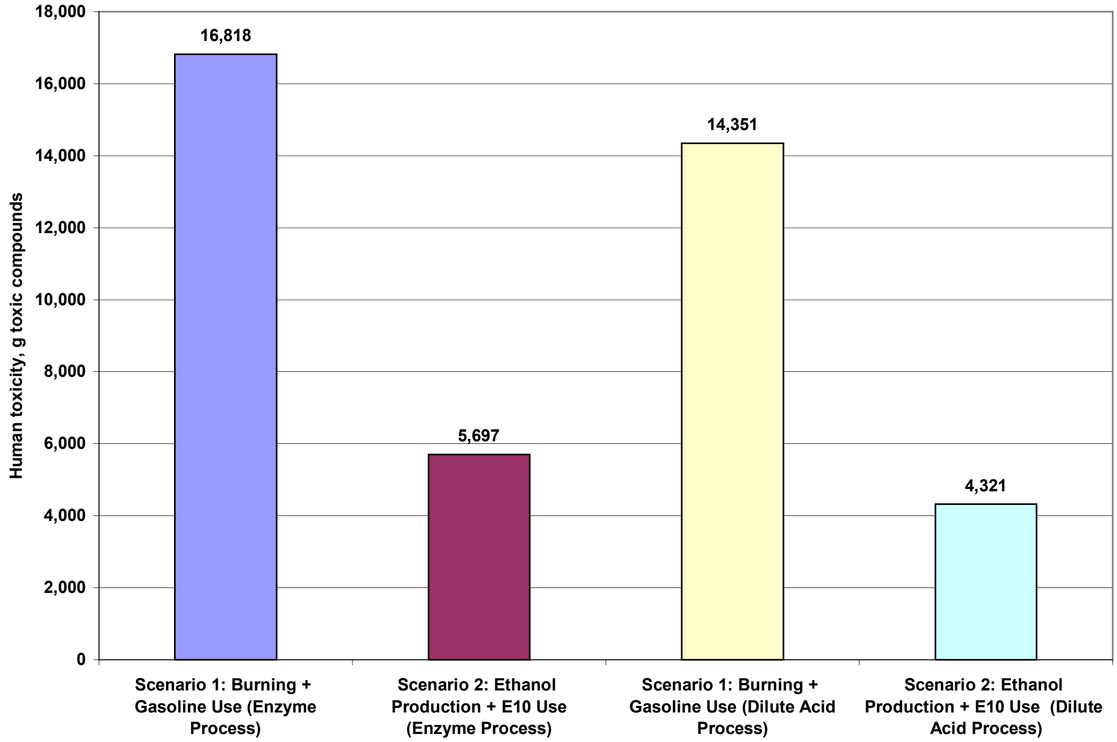

Figure 26. Comparison of burning versus diverting bagasse to ethanol: Human toxicity potential.

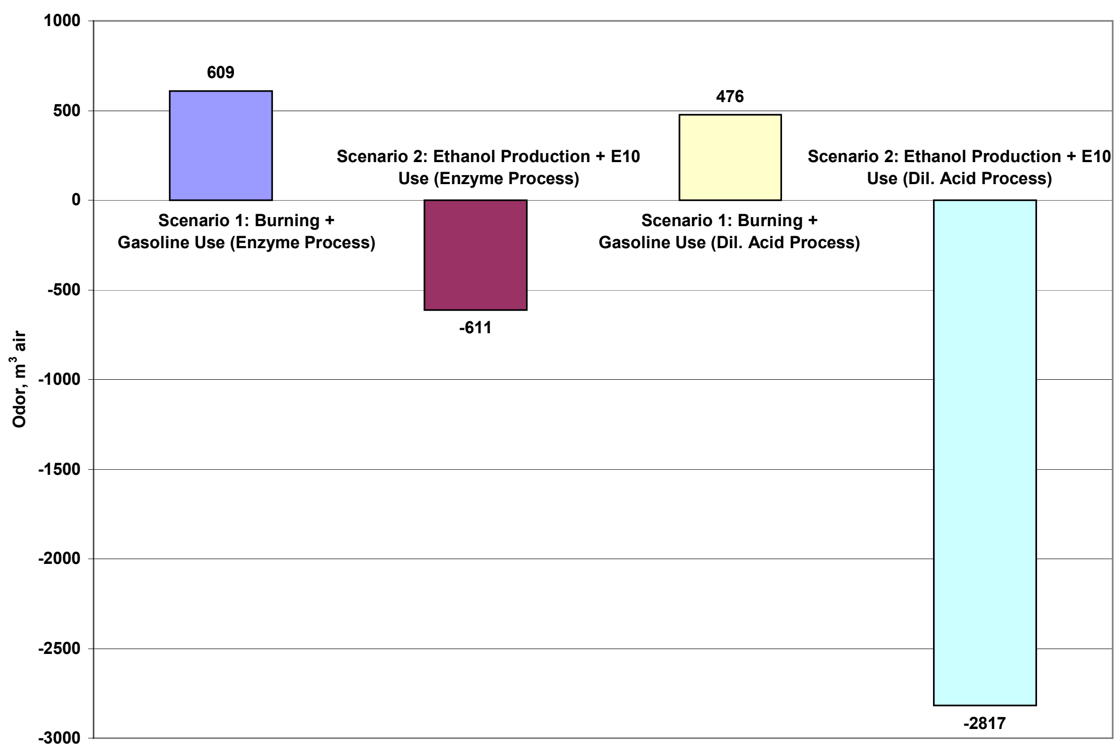

Figure 27. Comparison of burning versus diverting bagasse to ethanol: Air odor potential.

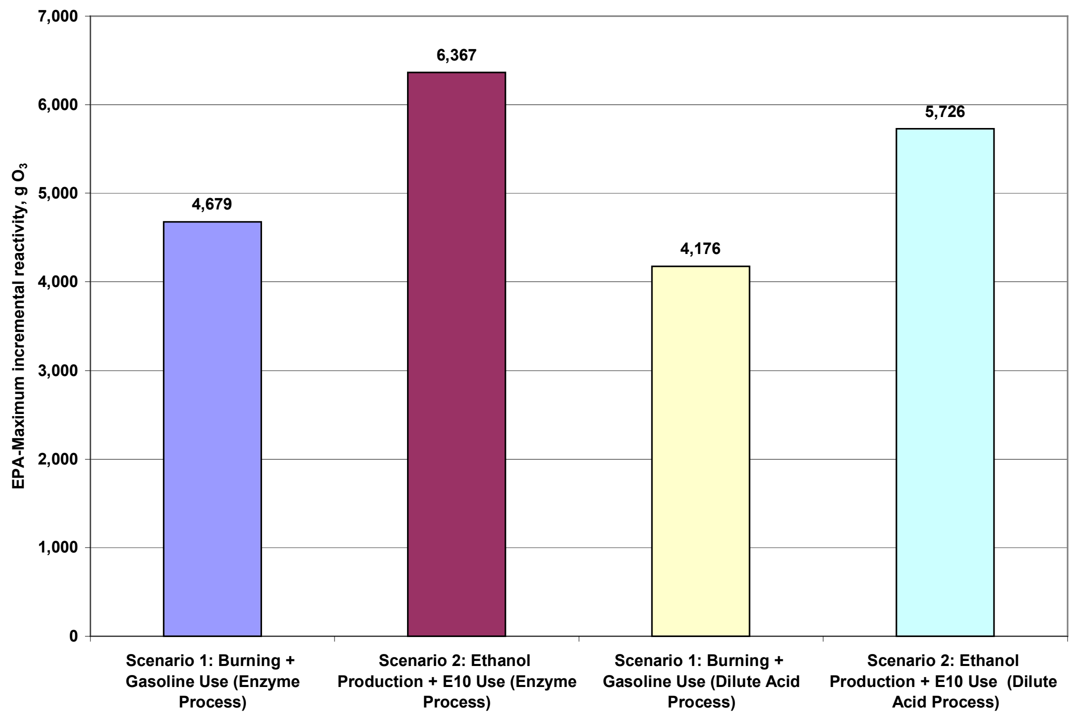

Figure 28. Comparison of burning versus diverting bagasse to ethanol: EPA-Maximum incremental reactivity potential.

10 CONCLUSION

This study provides specific quantitative data on environmental implications of bagasse disposal options in Maharashtra. The LCA performed in this study demonstrates the potentially significant benefits of using ethanol derived from bagasse. Overall, the results show that there is a significant difference between Scenarios 1 and 2 (burning as a disposal option versus conversion to ethanol, respectively); the magnitude of this difference varies with the type ethanol production process. However, in all cases, the comparison of Scenario 1 with Scenario 2 revealed a fundamental difference in energy derived from renewable sources, and the concomitant benefits of reduced greenhouse gas emissions.

Specifically, the prevailing trends observed for the ethanol scenarios were lower net values for:

- CO
- Hydrocarbons (except methane)
- SO_x and NO_x
- Particulates
- CO_2 and methane
- Fossil energy consumption

Hence, important advantages are associated with the ethanol scenario in regard to reductions in air emissions and energy consumption, and implementation of the ethanol scenario would facilitate air quality improvement. In terms of water phase emissions, however, COD levels were somewhat higher for the ethanol scenario. This is due to the use of ammonia during ethanol fermentation. The lower carbon dioxide and methane emissions, although not regulated or mandated by state or national laws, are desirable attributes. The lower greenhouse potential of Scenario 2 can be important if GHG trading is possible or in the case of JI because India is a developing country.

Additional drivers for the ethanol scenario are the lower values observed for the following six impact assessment categories: eutrophication potential, depletion of natural resources, greenhouse potential, air acidification potential, human toxicity potential, and air odor potential. It should be emphasized that the ethanol scenario shows a lower eutrophication potential despite higher COD values. With properly speciated data, ozone-forming potential can also be shown to be lower for the ethanol scenario.

Hence, the ethanol scenario is shown to commonly exhibit lower burdens than the burning scenario for key environmental criteria, both regulated and unregulated.

11 NEXT PHASE OF THE PROJECT

This study conclusively demonstrates the benefits of diverting the excess bagasse from burning to ethanol production. The next phase should address how to deploy this option in India. The deployment action plan would involve further investigation with the help of relevant parties and stakeholders in India, from both the public and private sectors. These are: the Ministry of Petroleum and National Gas, Indian Institute of Petroleum, Ministry of Surface Transport, Automotive Research Association of India (ARAI), sugar mills associations, potential manufacturers, nongovernmental organizations (NGOs) like USAID and Winrock International, provincial governments, and Petroleum Conservation & Research Association (PCRA).

There have been recent developments in India that bode well for this opportunity. In March 2000, India’s Minister of Petroleum and Natural Gas, Mr. Ram Naik, approved the use of ethanol to reduce detrimental air emissions. Ethanol is to be produced from sugarcane and other agricultural residues such as bagasse and used as an additive to gasoline. (Addresses of several alcohol manufacturers in Maharashtra are listed in Appendix C.) Three pilot projects will be launched in Maharashtra, Uttar Pradesh, and Tamil Nadu. The approval was announced after a seminar entitled, “Ethanol 2000: Sustainable Fuel for the Transport Sector” held in New Delhi. India’s Minister for Chemicals and Fertilizers, Mr. Suresh Prabhu, cited applications of ethanol use in the United States, France, Sweden, and Brazil as reasons why the country decided to adopt the use of ethanol. He also said, “One of the most promising strategies is the use of ethanol as a renewable fuel to reduce environmental pollution from India’s transport sector while creating new jobs in the rural communities.” (Winrock International 2000)

JI and CDM initiatives, and emissions trading are avenues available under the United Nations Framework Convention on Climate Change that can help deploy the renewable fuel option. The World Bank has started a Prototype Carbon Fund (PCF) to address climate change and promote the transfer of finance and climate-friendly technology to developing countries (World Bank 2000). This is the world's first international market-based emissions trading mechanism (CO_2, CH_4, N_2O, hydrofluorocarbons (HFCs), perflourocarbons (PFCs), and sulfur hexaflouride (SF_6)). A primary focus will be renewable energy technologies—such as wind, small-hydro, and biomass energy technology, which are not profitable without revenue from emissions reductions sold to the PCF.

During his recent trip to India, President Clinton signed a joint statement on cooperation in energy and environment between India and the United States that includes language about the CDM under the auspices of the Kyoto Protocol. Under the agreement, India and the United States will "work together and with other countries in appropriate multilateral fora towards early agreement on the elements in the Kyoto mechanisms, including the Clean Development Mechanisms.…" Although officials have not yet resolved some of the details of the CDM, the provision would allow developed countries to receive GHG emission reduction credits for investments made in GHG emission reduction projects in developing countries (IPS 2000).

Hence, these encouraging developments can be exploited in advancing the deployment of the bioethanol option in India.

LIST OF ACRONYMS AND ABBREVIATIONS

ARAI	Automotive Research Association of India
CDM	Clean Development Mechanism
CH_4	methane
CO	carbon monoxide
CO_2	carbon dioxide
CSL	corn steep liquor
g	gram
gal/yr	gallons per year
GHGs	greenhouse gases
ha	hectare
HMF	hydroxyl-methyl-furfural
JI	Joint Implementation
kg	kilogram
kJ	kilojoules
L	liters
L/yr	liters per year
LCA	life cycle assessment
LCI	life cycle inventory
LCIA	life cycle impact assessment
MJ	megajoules
mm	millimeters
Mt	million metric tons
MTBE	methyl tertiary butyl ether
N_2O	nitrous oxide
NGO	nongovernmental organization
NO_x	nitrogen oxides
OECD	Organization for Economic Cooperation and Development
PCF	Prototype Carbon Fund
PCRA	Petroleum Conservation & Research Association
SHF	separate hydrolysis and fermentation
SO_x	sulfur oxides
SSCF	simultaneous saccharification and cofermentation
t	metric ton
TPD	metric tons crushed per day
TRI	U.S. Toxic Release Inventory
EPA	U.S. Environmental Protection Agency
USAID	U.S. Agency for International Development
VOC	volatile organic compound
VSSK	Vasantdada Shetkari Sakhar Karkhana, Ltd.

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APPENDIX A: PROJECT REVIEW

The project was conducted in such a manner as to allow feedback. The Scoping & Data Summary Document was reviewed by Vince Camobreco and John Sheehan, and their comments were incorporated into the analysis. The draft Final Report (which contained the LCA results, as well as the scoping decisions and data summary) was reviewed by the following panel, comprised of experts specializing in various relevant fields such as biomass/bioenergy, alternative fuels, electricity generation (especially, in India), and LCA.

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[4]Was sent a draft for review but did not provide comments.

APPENDIX B: IMPACT ASSESSMENT

Background

Only recently has the LCA tool actually been concerned with the impacts on the environment of a system. By definition, the inventory component of an LCA, still the single focus of many LCA studies, is only concerned with the flows generated by the system (either consumed or emitted), and by definition, does not address the impacts on the environment.

In the most straightforward and transparent approach to LCI interpretation, the LCI results may be used *as-is* to help identify and prioritize opportunities for pollution prevention or increases in material and energy efficiency for processes within the life cycle. A particular advantage of LCI applied in this way is its comprehensiveness. LCAs help detect the shifting of environmental burdens from one life cycle stage to another (e.g., lower energy consumption during use, achieved at the cost of much higher manufacturing energy consumption), or from one media to another (e.g., lower air emissions at the cost of increased solid waste). The subsequent stage, LCIA, addresses the issue of how to translate the flows previously compiled into environmental impacts. Some issues viewed as crucial for LCIA are:

- The amount of additional exposure data that would be needed to model actual impacts (as in human health risk assessment) is technically incompatible with the nature of LCA (several hundreds or thousands of processes connected together, each one generating dozens or hundreds of emissions), and does not correspond to its objectives. It should be recognized that LCA is one environmental management tool among several, and that LCA cannot replace a specific environmental impact analysis for a specific site (see Figure 29).
- Because LCIA aims at assessing potential impacts, LCA should not be considered as a predictive tool for assessing the actual impacts associated with a system, but rather as a tool providing comparative results for the functional unit considered. Moreover, the functional unit has often no reference to time or space considerations (which would be needed for predictive models), but is solely related to the function and performance of a system. As the modeling of environmental impacts improves, potential LCIA models should become more and more precise and integrate crucial notions such as thresholds. (Current approaches are all based on a "less-is-better" approach.) Consequently, inventory data collection requirements could gradually increase with new parameters characterizing emissions' location, flow rate, key attributes of impacted media, etc.
- Existing approaches that result in a limited number of indices are highly controversial. They have been criticized because they do not separate the objective evaluation stage of the environmental impact on scientific grounds from the subjective "valuation" stage in which these impacts are traded off. Using such approaches is very dangerous from an industrial perspective, due to the following reasons.
  - It tends to favor short-term arbitrary choices while masking their arbitrary nature behind quantitative approaches, which convey more rigor and objectivity than are truly involved. This is incompatible with industrial long-term investment and product design.
  - The choices made might hide pollution displacement from one media to another or from one step to another. In numerous cases, results of inventory or impact assessment have

been conclusive enough so that no valuation was actually needed. Moreover, very often, the existence of trade-offs is by itself a crucial piece of information.

- For most impact categories, variability and uncertainties about impact potentials make any single numerical "equivalency factor" immediately contradictable and discreditable. Instead, LCIA methods need to be developed in which process data and results are considered in probabilistic terms. As for inventory results, uncertainties should be propagated and communicated to the decision-making audience.

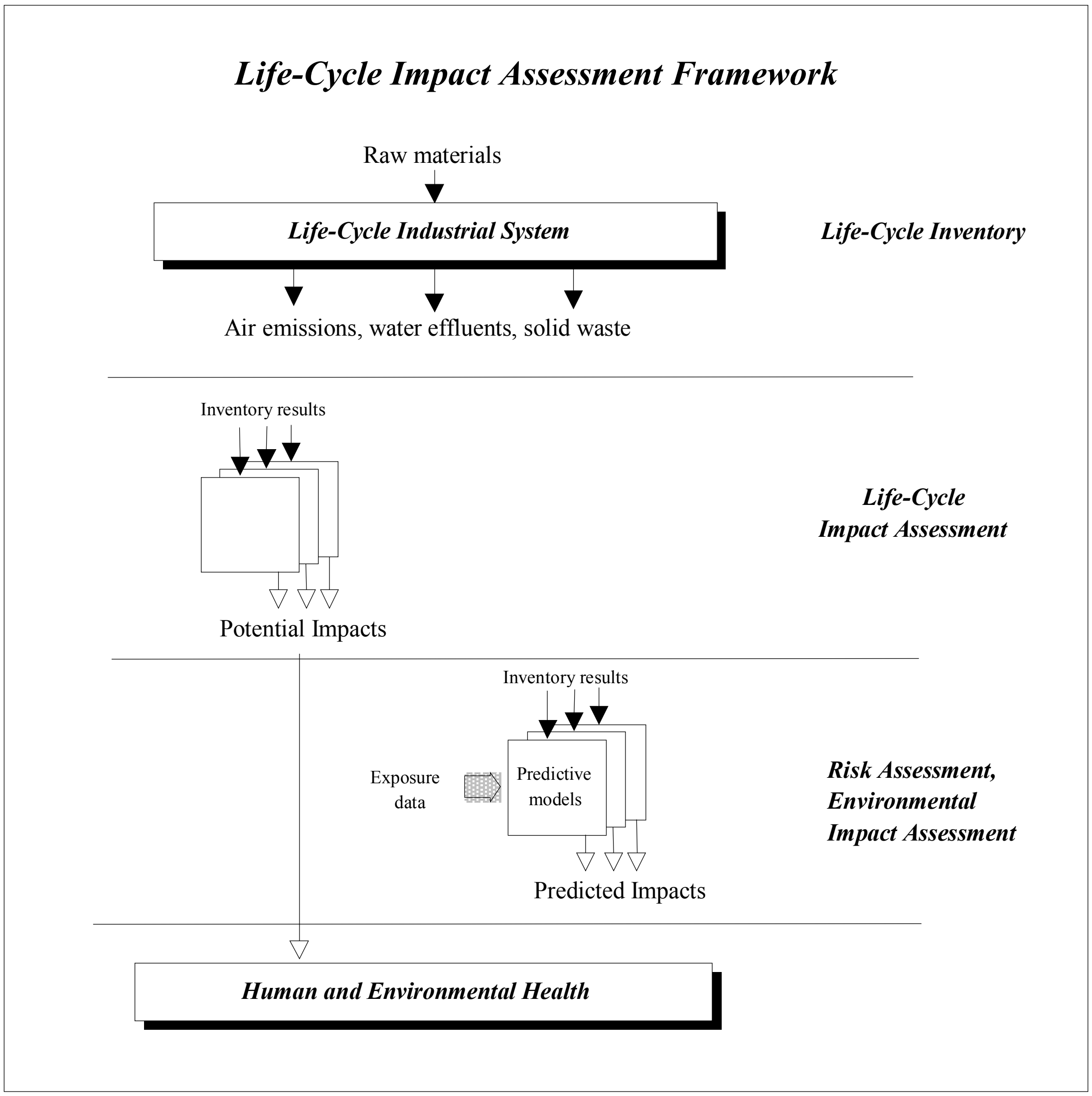

Figure 29. Life cycle impact assessment framework.

Overview of Life Cycle Impact Assessment Indices

Greenhouse Potential

The Greenhouse potential refers to the ability of some atmospheric gases to retain heat that is radiating from the earth. Models have been developed to quantify the contribution made by emissions of various substances to the greenhouse potential. Generally these models provide an indication of the change in the heat radiation absorption of the atmosphere. Global warming potentials (GWPs) have been calculated to compare the emission of different greenhouse gases (IPCC 1994).

The overall result of emission of these gases on the Greenhouse Potential (E) is calculated as follows:

$$E = \sum GWP_i \ x \ m_i$$

where, for a greenhouse gas *i*,

m_i: the mass of the gas released (in kg),

GWP_i: its potential impact on global warming expressed in grams of CO_2 equivalent.

The following factors are used to calculate the greenhouse potential (Table 27).

Table 27. Greenhouse gas potential factors

Formula	Substance	GWP_i
CO_2	Carbon dioxide	1
CH_4	Methane	21
N_2O	Nitrous oxide	310
CCl_4	Carbon tetrachloride	1,400
$CFCl_3$	CFC 11	4,000

The potential impact on global warming of the gas *i* can be defined as the ratio between the cumulative radiative force between the present and a future time horizon (in this case, 20, 100, and 500 years) as a result of the release of a unit mass of greenhouse gas *i* now, and an equal emission of the standard gas, CO_2. The calculation of the GWP is based on understanding the fate of the emitted gas and the radiative effect associated with the amount remaining in the atmosphere.

Acidification Potential

Potential acidic deposition (onto soil, vegetation, and water) can be expressed as potential H^+ equivalents. Potentially acidifying emissions of SO_2, NO_x, and NH_x can be aggregated on the basis of their potential to form H^+. In the calculation of H^+ equivalents, it is assumed that one mole SO_2 will produce two moles H^+, that one mole nitrogen oxide compounds (NO_x) will produce one mole H^+, and that one mole reduced nitrogen compounds (NH_x) will produce one mole H^+.

An acidification potential (AP) of a substance is calculated on the basis of the number of H^+ ions that can be produced per mole, given by the stoichiometry of the oxidation reaction (Guinee 1995). However, as emissions are specified in kg rather than in moles, the weight has to be divided by the molecular weight of the substance.

The factors used for AP are listed in Table 28.

Table 28. Acidification potential reactions

Formula	Substance	Reaction	AP
SO_2	Sulfur dioxide	$SO_2 + H_2O + O_3 \rightarrow 2H^+ + SO_4^{2-} + O_2$	32
NO_x	Nitrogen oxides	$NO_2 + OH^- \rightarrow H^+ + NO_3^-$	46
NH_3	Ammonia	$NH_3 + 2O_2 \rightarrow H^+ + NO_3^- + H_2O$	17
HCl	Hydrochloric acid	$HCl \rightarrow H^+ + Cl^-$	36.5
HF	Hydrogen fluoride	$HF \rightarrow H^+ + F^-$	20

Eutrophication Potential

Eutrophication is the addition of mineral nutrients to the soil or water, which increases production of cell biomass. In both media, the addition of mineral nutrients (N and P) in large quantities result in generally undesirable shifts in the number of species in ecosystems and a reduction in the ecological diversity. In water, it tends to increase algae growth, that eventually die and sink to the deeper layers of the water body. The decomposition of this dead cell biomass requires the consumption of large amounts of oxygen, which can result in the death of other aquatic species, such as fish.

Another form of oxygen deficit may be caused by emissions of organic materials that can bind oxygen. These emissions are generally expressed as BOD or the COD. The oxygen is mainly consumed by the biological degradation of organic content. The eutrophication potential (EP) of a substance is calculated on the basis of its potential cell biomass formation. It is calculated in N equivalent, by considering the average ratio of N and P in cell biomass and the oxygen required for the breakdown of this cell biomass. The ratios for N, P, and O_2 are 7, 1, and 142, respectively.

EPs are developed by analogy with the GWP. Therefore, phosphate ions have been chosen as the reference substance. A single index is produced for the eutrophication:

$$EP = \sum EP_i \ x \ m_i$$

where m_i is the weight (in kg) of the substance released. The calculated quantity indicates the quantity of a PO_4 emission with the same potential eutrophication effect.

The following classification factors (Table 29) are used for the eutrophication potential (CML 1992).

Table 29. Eutrophication potential factors

Formula	Substance	EP
PO_4	Phosphates	1
P	Phosphorous	3.06
N	Nitrogen	0.42
NO_x	Nitrogen oxides	0.2
NH_3	Ammonia	0.42
COD	Chemical oxygen demand	0.022

Natural Resources Depletion Index

Resource Depletion as an Environmental Issue

Resource depletion can be defined as the decreasing availability of natural resources. The resources considered in this impact are fossil and mineral resources, excluding biotic resources and associated impacts such as species extinction and loss of biodiversity. It is important to recognize that what is addressed in this index is the fact that some resources are depleted, not the fact that their extraction from the environment will generate impacts (e.g., methane emissions from coal mining).

Corresponding Inventory Flows

The assessment of natural resources depletion can only be applied to a subset of the LCI flows called elementary flows, i.e., flows that are directly taken from the environment. A coal consumption of 1 kg at the power plant gate does not correspond to an elementary flow. Rather, it corresponds to a consumption of approximately 1.03 kg of coal in the ground, due to the losses in mining, processing, and transportation.

Availability Defined

The notion of availability can be further defined. Natural resources depletion does not consider the availability within the economy, but rather within the "natural" environment. Excluded from this impact are "economic stocks" such as aluminum from aluminum cans or steel from used car bodies. Therefore, the availability is not measured within the whole economy, but only at the economy-environment "boundary." Furthermore, the availability is concerned with the availability within the primary extraction medium (e.g., iron ore available from the earth's crust) and not within the entire geosphere (which would include iron available in water bodies, atmosphere, plants, landfills, etc.).

Resource versus Reserve

Once the concept of availability has been defined, the notion of reserve of a resource needs also to be determined. Through the years, geologists, mining engineers, and others operating in the mineral field have used various terms to describe and classify mineral resources. Known resources can be classified from two standpoints: 1) purely geologic or physicochemical characteristics—such as grade, tonnage, thickness, and depth—of the material in place, and 2) profitability analyses based on costs of extracting and marketing the material in a given economy at a given time. The former constitutes important objective scientific information of the resource and a relatively unchanging foundation upon which the latter economic delineation can be based. For mineral resources, the reserve chosen for this index is the reserve base as defined by the U.S. Bureau of Mines resource (USDOI 1994): "part of an identified[5] resource that meets specified minimum physical and chemical criteria related to current mining and production practices, including those for grade, quality, thickness, and depth. The reserve base encompasses those parts of the resources that have a reasonable potential for becoming economically available within planning horizons beyond those that assume proven technology and current economics. It includes those resources that are currently economic (reserve), marginally economic (marginal reserves) and currently sub-economic." By including economic and sub-economic considerations, the reserve base falls between the two extremes of economic reserve and ultimate reserve/resource base.

For fossil fuels (including uranium), the reserve chosen is based on information supplied by the World Energy Council (WEC). In order to be consistent with the reserve base used by the U.S. Bureau of Mines, the reserve chosen for fossil fuels has been defined as the addition of the WEC's "proved amount in place" (tonnage in place that has been both carefully measured and has also been assessed as exploitable under present and expected local economic conditions with existing available technology) and "estimated additional reserves recoverable" (quantity of the estimated additional amount in place that might become recoverable within foreseeable economic and technological limits).

It should be noted that what matters most in this impact assessment index is the availability of a *relative* scale allowing comparisons between resources rather than an estimation of the exact size of what is considered available for use. This is linked to the fact that Impact Assessment as performed within an LCA is of a comparative rather than predictive nature. It aims at assessing the relative potential impacts of different alternatives (i.e., natural resource depletion index of A versus B) rather than assessing the actual impacts of a system onto the environment (as it would be done in traditional risk assessment).

Index Definition

Once the type of reserve is identified, an index can be defined that will relate an inventory flow with the depletion of that resource. The proposed depletion index uses equivalency factors, i.e., each natural resource consumption recorded in the inventory is multiplied by the resource's weighting factor (or equivalency factor). As described in equation (1) that follows, the total depletion index is then compiled by adding the previous intermediate results for all inventory flows considered.

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[5]As opposed to identified resources are undiscovered resources, the existence of which is only postulated.

Several methods can be used to produce the equivalency factors. In the first method described in equation (2), the inverse of reserve (in kg) is used as a weighting factor. Such an index addresses the relative contribution of the LCA system to the depletion of the reserves (the larger the relative contribution, the bigger the index) as well as the size of the reserve (the larger the reserve, the smaller the index). However, it does not address the following problem: how long a given resource will continue to be available (the fact that the reserve is rapidly or slowly being depleted, which is directly related to the notion of sustainability, is not accounted for in this index).

In the second method, described in equation (3), the inverse of remaining years of use is used as a weighting factor. The number of remaining years of use is defined as the reserves divided by the total world-wide production (i.e., extraction). It represents the number of years for which current reserves will suffice at the current production (extraction) level. This index, however, does not correctly account for the size of the reserve: two resources with the same number of years will have the same indices irrespective of whether there are 1 kg or 1 million t reserves.

In the third method described in equation (4) and retained as a basis for the index, the inverse of remaining years of use <u>and</u> the reserve size are used as weighting factors. This index addresses both problems that were raised by the first two methods. It should be noted, however, that choosing higher (e.g. cubic) power for the reserve and production could generate a number of similar indices.[6] Because there is no rational basis for doing so, the index has been kept as in equation (4). In order to facilitate the readability of the results, all equivalency factors have been multiplied by 10^{15}. (As explained previously, the relative contribution of each resource is what matters most.)

$$(1)\quad Depletion = \sum_{res} equivalency\ factor_{res}\ \text{x}\ inventory\ consumption_{res}$$

$$(2)\quad Depletion = \sum_{res} \frac{1}{reserve_{res}}\ \text{x}\ inventory\ consumption_{res}$$

$$(3)\quad Depletion = \sum_{res} \frac{1}{years_{res}}\ \text{x}\ inventory\ consumption_{res} = \sum_{res} \frac{production_{res}}{reserve_{res}}\ \text{x}\ inventory\ consumption_{res}$$

$$(4)\quad Depletion = \sum_{res} \frac{1}{reserve_{res}\ \text{x}\ years_{res}}\ \text{x}\ inventory\ consumption_{res} = \sum_{res} \frac{production_{res}}{\left(reserve_{res}\right)^2}\ \text{x}\ inventory\ consumption_{res}$$

Human Toxicity Index

Human toxicity potential (HTP), expressed in kg of body weight, is calculated as follows:

$$HTP = \sum HCA_i mA_i + \sum HCW_i mW_i + \sum HCS_i mS_i$$

[6] It has been shown that in order to keep the index independent of the resource density, the power of the reserve should be the power of the production plus one, which is the case in equation (4).

where, for the toxic compound *i*,

mA_i: the mass (in g) of a compound emitted in air,
$mS_{i:}$ the mass (in g) of a compound emitted in soil,
mW_i: the mass (in g) of a compound emitted in water,
$HCA_{i:}$ the toxicological Classification Factor (in kg body weight/g substance) for air emissions,
HCS_i: the toxicological Classification Factor (in kg body weight/g substance) for soil emissions,
HCW_i: the toxicological Classification Factor (in kg body weight/g substance) for water emissions.

The factors applied to the amounts of substances emitted in the environment are the products of two factors: the exposure factor and the effect factor.

For an emission of a substance $M_{subs,air}$ in the air:

$$C_{subs,air} = \frac{M_{rsubs,air}}{V_{air}}$$

$$m_{subs,via\_air} = \frac{M_{subs,air}}{V_{air}} v_{air}$$

$$T_{subs,via\_air} = \frac{M_{subs,air}}{V_{air}} v_{air} W$$

The exposure factor of a substance emitted in air is independent of this substance and is equal to:

$$X_{subs,via\_air} = \frac{v_{air} W}{V_{air}}$$

where,

$M_{subs,\ air}$ (in kg substance): quantity of the substance *subs* emitted in the air
C_{subs}, air (in kg substance/m3): atmospheric concentration of subs
V_{air} (m^3): total volume of air in the world model ($3x10^8$ m^3)
v_{air} (in m^3/day/person): volume of air inhaled per person per day
m_{subs,via_air} (in kg substance/day/person): total daily human exposure
W (in person): global population
$T_{subs,\ via\_air}$ (in kg substance/day): total daily exposure
$X_{subs,\ via\_air}$ (in day^{-1}): exposure factor air

The calculation for water is analogous to the one for the air, with:

V_{water} (m^3): total volume of water in the world model (3.5×10^{18} l) and v_{water} (in l/day/person): volume of water consumed per person per day

The case of soil is different as soil is not directly consumed by human beings. Nevertheless, a parameter v_{soil} is introduced: v_{soil} is analogous to the volume of air inhaled (per person and per day) or to the human water consumption consumed (per person and per day) and is expressed in kg soil/kg body weight/day. This parameter was evaluated based on a study carried out by the National Institute of Public Health and Environmental Protection (RIVM) in Bilthoven, The Netherlands). The concentration C in soil was calculated for a number of substances, which should not be exceeded to not threaten public health. A serious threat to the public health corresponds to a dose for a person equal to the product of TDI x M x N (TDI: Tolerable Daily Intake, in kg substance/kg body weight/day; M: body weight of a person; N: corrective factor).

By analogy with the exposure factors for air and water, this dose (TDI x M x N) may be set equal to C x v_{soil} where v_{soil} is expressed in kg soil/person/day.

$$m_{subs,via\_soil} = TDI \times M \times N = C \times v_{soil}$$

$$v_{soil} = \frac{TDI \times M \times N}{C}$$

$$X_{subs,via\_soil} = \frac{v_{soil} W}{V_{soil}}$$

The parameter v_{soil} is used as a "quantity of soil consumed by a person during a day." It varies from one substance to another (TDI depends on the substance). As the dose reaching humans is proportional to the quantity emitted, this calculation assumes that the exposure route is independent of the level of emission.

The exposure factor of a substance emitted in soil is equal to:

$$E_s = \frac{1}{TDI}$$

TDI (in kg substance/day/kg body weight): tolerable daily intake

According to the data available, the effect factor for a substance emitted in the air is equal to (in order of preference):

$$E_{air} = \frac{M}{TCL \times v_{air}} \qquad \frac{M}{AQG \times v_{air}} \qquad \frac{1}{TDI} \qquad \frac{1}{ADI}$$

(1) (2) (3) (4)

where,

M (in kg body weight): body weight of a person
TCL (in kg substance/m^3): acceptable concentration in air
AQG (in kg substance/m^3): air quality guidelines
TDI (in kg substance/day/kg body weight): tolerable daily intake
ADI (in kg substance/day/kg body weight): acceptable daily intake
v_{air} (in m^3/day/person): volume of air inhaled per person per day
TCL: Set by RIVM. The health effects of continuous daily exposure by inhalation to air polluted to the level of the TCL are assumed to be equivalent to a daily oral dose equal to the TDI of that substance.
AQG: Air Quality Guidelines set by the World Health Organization (WHO).
TDI: Tolerable Daily Intake set by RIVM. The WHO method used for ADI was applied for the harmfulness of a substance for oral exposure.
ADI: Acceptable Daily Intake set by WHO.

It should be noticed that TDI and TCL are calculated by extrapolation of data from animal studies. These data (NOEC, LC50, etc.) are divided by uncertainty factors that vary from one method to another. These factors have no scientific meaning and induce a distortion in the results. When there is no threshold value, for instance, in the case of carcinogenic substances, the maximum tolerable risk is equal to 1 additional cancer per 10,000 individuals exposed.

$$E_s = \frac{1}{TDI}$$

According to the data available, the effect factor for soil is equal to:

where,

TDI (in kg substance/day/kg body weight): tolerable daily intake
ADI (in kg substance/day/kg body weight): acceptable daily intake

According to the data available, the effect factor for water is equal to (in order of preference):

$$E_w = \frac{1}{TDI} \qquad \frac{1}{ADI}$$

(1) (2)

where,

TDI (in kg substance/day/kg body weight): tolerable daily intake
ADI (in kg substance/day/kg body weight): acceptable daily intake

Stratospheric Ozone Depletion Index

The ozone (O_3) layer is present in the stratosphere and acts as a filter, absorbing harmful short-wave ultraviolet light while allowing longer wavelengths to pass through. Since the late 1970s, a thinning of the ozone layer over the Antarctic has been observed during the spring, which could amount to up to 80%-98% removal of this layer (the ozone "hole"). This hole over the Antarctic is created by the unique chemistry present over the poles. During the winter, a cyclonic vortex forms over the Antarctic, within which temperatures become very cold (less than -80°C), which allows the formation of 'polar stratospheric clouds' (PSCs). Most chlorine and bromine (from CFCs and other sources) in the atmosphere are bound in reservoir compounds, which render them inert and unable to affect ozone. However, in the presence of the PSCs, complex reactions occur that release active chlorine and bromine from the reservoir compounds. The addition of ultraviolet light during the spring sets up catalytic reactions involving chlorine and bromine, which result in ozone depletion. As the vortex breaks down, this ozone-depleted air mixes into the rest of the stratosphere. These reactions occur, to a lesser extent, in the Arctic.

A decline in the ozone layer allows more harmful short-wave radiation to reach the earth's surface, potentially causing changes to ecosystems as different flora and fauna have varying abilities to cope with it. There may also be adverse affects to agricultural productivity. Effects on humans can include increased skin cancer rates (particularly the fatal melanoma type) and eye cataracts, as well as suppression of the immune system. Another potential problem is the uncertain effect on the climate.

Index Calculation

The inventory data assigned to the Tropospheric Ozone Creation Index are the VOCs emitted in the air. However, all the VOCs for which an MIR is available have not been included. Also, in this method, there is no coefficient for chemical families, such as alkanes, halogenated hydrocarbons, alcohols, etc., as well as for hydrocarbons (unspecified). Only very specific pollutants are taken into account.

The overall result of emission of these gases on the MIR index is calculated as follows (Carter 1994):

$$E = \sum MIR_i \times m_i$$

where, for a volatile organic compound gas *i*,

m_i: mass of the gas released (in kg),
MIR_i: its Maximum Incremental Reactivity.

There are a number of inherent difficulties in calculating VOC reactivities, not the least of which is the nonlinear nature of the reactions in photochemical smog. This is typified by the actions of NO_x, which can either form O_3 or inhibit its formation, depending on the overall environmental conditions. Additionally, scientists are still not certain of the exact mechanism for ozone formation.

One method that is used to quantify the ozone production potential of various VOCs is the incremental reactivity (IR) scale. This scale gives values for VOCs that indicate the change in ozone caused by adding a small amount of the compound to the emissions, divided by the amount added. More precisely, the incremental reactivity is a function of the product of a VOC's kinetic and mechanistic reactivities:

kinetic reactivity mechanistic reactivity mass conversion
IR = (VOC reacted/VOC emitted) x (moles O*3*/mole VOC reacted) x (moles VOC/gram VOC)

The kinetic reactivity is a value that is primarily dependent on the VOC's atmospheric rate constants as well as the overall levels of OH radicals, ozone, or light in the scenario. The mechanistic reactivity is a component of both the compound's reaction mechanism and its efficiency in forming ozone. Because most VOCs are measured in terms of mass, a mass conversion component is added. The resulting value is generally given in terms of moles of O_3 formed per gram of VOC emitted.

Obviously the calculation of incremental reactivity values is dependent on an understanding of both reactivity of the VOC and the environmental conditions during the time period studied. Therefore, there are limits to the accuracy of the calculated IR values. All the same, government bodies have generally accepted incremental reactivity values.

In the calculation of IR values, a base mix of organic gases is defined in order to approximate the atmospheric constituents. Different scenarios are then modeled to reflect changes in NO_x concentrations and VOC emissions, to determine the effects on ozone production. One scenario, which gives the MIR, is modeled using the environmental conditions at which the peak ozone levels are most sensitive to changes in total reactive VOC emissions. Results from the MIR scenario are often preferred, because even if environmental conditions vary widely, the incremental reactivity for the VOC will most likely not be more than that which was determine under MIR.

Officially, the EPA has a policy that ranks volatile organic compounds as being either "negligibly reactive" and "reactive." These rankings are used for regulatory control purposes, but they are based on the reactivity of a compound. The informal policy is that compounds with incremental reactivities less than that for ethane (0.299 gram O_3 per gram VOCs) are considered 'negligibly reactive.' This is not to say that these compounds do not form ozone— they do. However, they just produce ozone at small enough levels that their effect on overall ozone formation is considered to be inconsequential.

Odor Index

An odor is a volatile emanation of a substance that triggers an olfactory feeling. Odor is considered a problem when a given concentration of odorous substances is experienced as unpleasant. Whether a smell will be experienced as odor (stench) will depend on the individual exposed to it. However, above a certain emission level all individuals will experience it as an odor.

Index Calculation

The potential direct odorous effects on individuals ('the Odorous Nuisances') of the emission of 64 'malodorous' substances are considered. The overall results of emission of these gases on the Odorous Nuisances in air (O_{air}), expressed in m^3, are calculated as follows:

$$O_{air} = \sum \frac{m_{i,air}}{OTV_{i,air}}$$

where, for an odorous gas *i*,

$m_{i,air}$: mass of the substance *i* released in air (in kg).
$OTV_{i,air}$: Odor Threshold Value in air (in $kg.m^{-3}$).

The Odor Threshold Value (OTV) of a substance is defined as the concentration of a given substance under defined standard conditions at which 50% of a representative sample of the population can just detect the difference between a sample of air mixed with that substance and a sample of clean air. Thus, this is a definition at the smell (this term is used for emissions) level not at the odor (or odor nuisance: this term is used for effects) level. Smell can be measured with some objectivity but individual associations become more important for odor (stench). For these reasons odor threshold - in fact smell threshold values - rather than stench threshold values are determined.

Odorous substance concentrations and potential odor nuisances are closely related. However, an odor emission does not necessary mean odor nuisance. An odor emission may or may not lead to potential stench or odor nuisance depending on the dispersion of the substance, chemical conversion, stack height, meteorological conditions and the distance between an emission source and a residential area. The provisional approach for malodorous air is a worst case approach, which does not take into account the dispersal and degradation processes, largely dependent on the substance concerned.

In the longer term, some of these processes could be included in the assessment of odor emissions to quantify the contribution of individual substances emissions to odor nuisances, relative to a reference substance.

For most substances, there is no uniform OTV. Today, many measurement methods are available; the purity of the substances, the rate at which the concentration rises, the number of subjects, etc., are also factors that influence the odor threshold value. As a result, the values available show wide differences and heterogeneity between OTVs.

Emissions of potentially malodorous substances to water could also produce malodorous air after evaporation into the atmosphere, but this process is not taken into account.

APPENDIX C: LIST OF ALCOHOL MANUFACTURERS IN MAHARASHTRA

1) The Andhra Sugars Ltd.
   Venkatraypuram, Tanuka, West Godavari Dist: A.P. 534215. Tel: 08819/2911, Fax: 3168.
   Capacity: 5,400 TPA.[1] Contact Person: M. Thimmaraja.

2) Ashok Organics Industries Ltd.
   406 Sharda Chambers, 33 New Marine Lines, Mumbai, 400 020. Tel: 2056410, 2089556,
   Fax: 2089456.

3) Alembic Chemicals Works Co. Ltd.
   Alembic Road Baroda 390 003. Tel: 330550, Fax: 330834
   Capacity: 3,000 TPA. J.H. Parikh, Manager–Marketing.

4) Cellulose Products of India Ltd.
   National Chambers, 29 Veer Nariman Road, Fort Mumbai 400 023. Tel: 2045598, 4835,
   Fax: 2043271.
   Capacity: 10 MLA.[2] Contact Person: G.D. Kamat, General Manager–Marketing.

5) Kothari Sugars & Chemicals Ltd.
   Kothari Building, 115, Mahatma Gandhi Salai, Chennai, 600 034. Tel: 8276036, 4901, 4892 ,
   Fax: 8272263.
   Capacity: 9 MLA. Contact Person: V. Ramchandran.

6) Krishna Sahakari Sakhar Karkhana Ltd.
   Rethare Budruk, P.O. Shivnagar, Karad Dist: Satara 415 108. Tel: Karad 2306, Shivnagar
   6222, 6226.
   Capacity: 4.4 MLA. Contact Person: R.T. Bhosale.

7) Somaiya Organics (India) Ltd.
   Narang house, 34, Cht. Shivaji Maharaj Marg, Mumbai 400 039. Tel: 2022934, 2852534,
   Fax: 2873646.
   Capacity: 600 TPA. Contact Person: K.S. Prasad.

8) Synthetics & Chemicals Ltd.
   Oriental House, 7 J Tata Road, Mumbai 400 020. Tel: 220161, Fax: 2870299. Capacity: 30
   MLA. Contact Person: Ketan/Varshal Krishnakant Parikh.

9) Kesar Enterprises Ltd.
   Tel: 2042396, 2851737, Fax: 2876162.
   Capacity: 14.3 MLA. Contact Person: S.S. Bhatia.

10) United Co-operative Distillery Ltd.
    Parite, Shahunagar, Parite Karvir Dist. Kolhapur 416211, Tel: 5630.
    Capacity: 4.5 MLA. Contact Person: P.G. Meghe.

11) Vijayshree Chemicals (India) Ltd.
201, Arvind Chambers, Sai Service Compound, W.E. Highway, Andheri (E), Mumbai 400 069. Tel: 8385304, 4984, Fax 8384984.
Contact Person: K. Chaturvedi.

12) Tilak Nagar Industries Ltd.
Industrial Assurance Building, Churchgate, Mumbai 400 020. Tel: 2831716/8, Fax: 2046904.
Capacity: 6 MLA, Contact Person: V.K. Nagle.

13) Sanjivani (Takli) S.S.K. Ltd.
Sahajanandnagar. P.O. Shingnapur Tal. Kopargaon Dist. Ahmadnagar 423 603. Tel: 2334, 2305, Fax: 0242324208.
Capacity: 65,000 liters per day. Contact Person: A.D. Antre.

[1]TPA: metric tons per annum
[2]MLA: million liters per annum

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13. ABSTRACT *(Maximum 200 words)*

Bagasse is the fibrous residue generated during sugar production and can be a desirable feedstock for fuel ethanol production. About 15%–25% of the bagasse is left after satisfying the mills' energy requirements, and this excess bagasse can be used in a bioconvesion process to make ethanol. It is estimated that a 23 million L/yr (~6 million gal/yr) ethanol facility is feasible by combining excess bagasse from three larger sugar mills in Maharashtra state. The plant could supply about half of the ethanol demand in Mumbai, assuming that all gasoline is sold as an E10 fuel, a blend of 90% gasoline and 10% ethanol by volume.

The life cycle assessment (LCA) performed in this study demonstrated the potentially significant benefits of diverting excess bagasse in Maharashtra to ethanol production, as opposed to disposing it by burning. In particular, lower net values for the ethanol production scenario were observed for the following: fossil energy consumption, and emissions of carbon monoxide, hydrocarbons (except methane), SO_x, NO_x, particulates, carbon dioxide, and methane. The lower greenhouse potential of the ethanol scenario is also important in the context of Clean Development Mechanism and Joint Implementation because India is a developing country.

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